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ROLL STABILITY OF GROUND EFFECT MACHINES - THICK ANNULAR JET AND PLENUM TYPES

FINAL REPORT

By
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June 1965

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-19(T)

NORMAN K. WALKER ASSOCIATES

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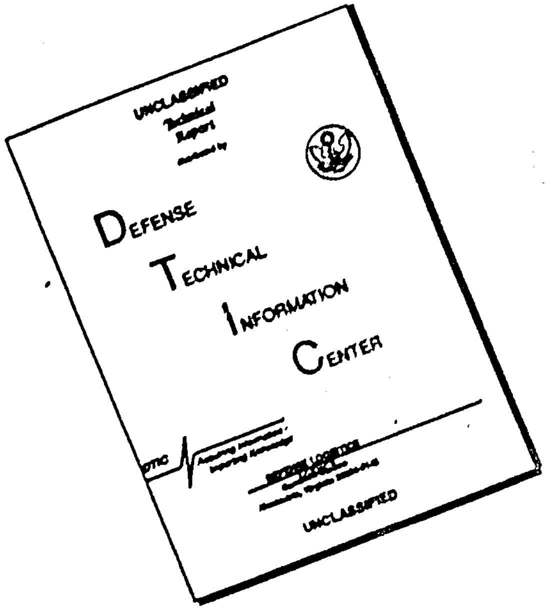

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The present study was undertaken to describe more accurately those characteristics of an air cushion vehicle that determine its roll stability and their relative influence.

It is one of two reports concerned with air cushion vehicle stability and dynamics prepared under contract DA-44-177-AMC-19(T).

The report has been reviewed by the U.S. Army Transportation Research Command, and the data contained in it are considered to be valid. The report is published for the dissemination of information.

NOTE

On 1 March 1965, *after this report had been prepared,* the name of this command was changed from U.S. Army Transportation Research Command to:

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FINAL REPORT

Norman K. Walker Assoc. Report No. 13

by
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SUMMARY

An electrically powered model Ground Effect Machine, first arranged with a thick annular jet and second as a simple plenum chamber, was used in an investigation of the roll stability in hovering flight.

The lift, height, and power relationship was determined and the restoring moment and side force due to inclination to the ground were measured. The dynamic stability was observed with the machine supported on pivots which were free to move sideways. These were first located close to the base of the model and then at intermediate and high positions above the base. Low and high positions of the model center of gravity (CG) were available. Finally, the model was flown without any constraints, in both versions and at both CG heights and at an extra high CG position with overload ballast.

In the annular jet version, the restoring moment was proportional to roll angle and changed little with flying height. The side force on body axes was zero at heights less than the jet width and slightly negative (that is, towards, the high side of the machine) at greater flying height. The plenum chamber version had little or no restoring moment but had positive side force, expressible as a rotation of the lift vector through an angle greater than the roll angle. This effect increased with height, from a ratio 1. 14 up to 1. 8 at the greatest height tested. Both versions were dynamically stable in their various ways and were little affected by the variation in CG height.

The addition of outward-curved fairings at the lower edges of the plenum chamber made the model strongly stable, with a finite restoring moment and a lift vector rotation to twice the roll angle, but reduced the hover height.

The experiments are illustrated by 20 diagrams and 4 photographs. The free flight tests were recorded on 200 feet of 16mm color film.

Some special cases of the skirted GEM with one side in contact with the ground are discussed in the appendix of this report.

PREFACE

The experimental work described in this report was performed by members of the staff of Norman K. Walker Associates at the firm's offices and laboratory at Bethesda, Maryland, during the period from May to September 1963.

The model GEM was adapted from one which had been built by the Hexicopter Model Research Company, Arvada, Colorado, and had been used in a previous investigation.

Mr. David A. Shaffer collected the data and prepared the material for the report. He was assisted by Mr. Richard Brooks who also made the alterations to the model and to the test equipment.

Mr. Norman K. Walker and Mr. Alastair Anthony supervised the work and edited the report. They contributed the analysis in the appendix and in the section headed 'Simple Theory'.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

a	beam or width of GEM base, between inside faces of sidewalls
b	length of GEM between inside faces of end walls
F	resistance of ground, water, or other obstacle
G	width of jet
G_e	effective width of jet = total jet area divided by periphery
g	gravitational constant = 981 centimeters per second per second
h	rise height, height of base of GEM above ground
I	moment of inertia of GEM in roll about CG
i	current supplied to drive motors
l	upwards dimension of GEM from lowest point
l_p	distance of free roll axis above base of machine
l_w	distance of center of gravity of machine above base
L	lift force exerted by GEM
M	aerodynamic moment about center of base
$\overline{M}_\phi$	nondimensional stiffness in roll, equal to $- M_\phi/La$
M_ϕ	rate of change of M with respect to ϕ
P	location of free roll axis
p_b	aerodynamic pressure on the base of the GEM
V_h	velocity of air leaving plenum GEM at height h
W	weight of GEM
y	distance sideways
Y	side force on level GEM against inclined ground
z	distance vertically downwards
ρ	density of air, grams.sec^2.cm^{-4}

ϕ angular displacement of GEM in roll

χ angular displacement of lift vector relative to GEM

χ_ϕ rate of change of χ with respect to ϕ, equal to rate of change of side force with respect to roll angle

ω angular frequency of oscillation

INTRODUCTION

This investigation is concerned with the fact that the lift on a Ground Effect Machine rotates with the machine as it rolls. This gives rise to the characteristic unique among surface vehicles: the stability in roll when flying clear of the ground is affected very little by the height of the center of gravity above the base of the machine.

In a previous investigation, this phenomenon was examined with a small GEM model constructed with a thin annular jet. It was found that the lift remained perpendicular to the base, so far as the experimental technique could detect, and certainly remained within 10 percent of the angle of roll. The model was actually flown with the center of gravity higher than one beam width above the base without any noticeable loss of stability.

Naturally it was desired to test this conclusion in a GEM model which exemplified features applicable to a full-scale practical GEM. Most designers, nowadays, are resorting to flexible skirts or trunks to allow the machine to ride over obstacles higher than the flying altitude. This directs interest toward thicker jets and toward the plenum chamber arrangement, since the hollow base of a GEM with jet extension in a partial approximation of a plenum chamber. The full plenum chamber design is also of interest in its own right, even if only academically, since it has been predicted that the lift of a plenum chamber rotates twice as much as the machine does and that it therefore exerts a restoring moment which is greater at the higher CG positions.

Accordingly, the United States Army Transportation Research Command (USATRECOM), Fort Eustis, Virginia, instructed the present authors to modify the model GEM by fitting a downward extension of its walls and a new base, thus representing a thick-jet GEM with trunks. It was decided to test this in a manner similar to what had been done with previous models. They desired the tests to be done also with the base removed in order to represent a full plenum chamber type of GEM. For good measure, the investigation further modified the plenum version with fairings in order to induce maximum lateral discharge of the jet and to set up experimentally the assumption on which the theoretical prediction of increased stability had been based.

CONCLUSIONS

The dynamic stability of a GEM in hovering flight when not in contact with the ground or other obstacles is governed by the moment of the aerodynamic forces about the center of gravity of the machine. These may be represented by a resultant lift force acting through the center of the base and a couple, or static moment, applied to the base.

For a GEM with a thick annular jet and comparatively small cross jets the static moment is finite and stabilizing, though not so large as when the annular jet is thin. For a plenum chamber GEM the static moment is generally small or nonexistent and does not increase with roll angle; therefore, it does not contribute to stability in roll.

The lift force rotates with the machine as it rolls. For the annular jet machine at a flying height of less than the jet thickness, the rotation is equal to that of the machine; no side force is developed, and, consequently, the stability is governed by the static moment alone and is not affected by height of the CG. At flying heights which are greater than the jet thickness, the rotation is somewhat less than the roll of the machine; consequently, there is a small negative side force which has destabilizing moment about the CG, particularly when this is high above the base. However, this effect is slight.

For the plenum chamber type of GEM, the rotation of the lift vector is greater than that of the machine at all altitudes; this is the cause of the machine's stability. The stabilizing effect increases as the CG height is increased.

The magnitude of the additional rotation of the lift is indicated by the side force coefficient χ_ϕ. A value $\chi_\phi = 1.0$ has been predicted for the plenum, but this is attained only when the sidewalls are faired outwards to give maximum lateral discharge. This diminishes lift but results in a highly stable machine. For the practical case with straight side walls the lateral discharge is governed by a discharge coefficient of less than unity. A value 0.6 is appropriate and this results in a value $\chi_\phi = 0.2$. The values measured range from 0.143 at $h/a = 0.033$ to 0.80 at $h/a = 0.91$ and the increase with height is attributed to higher values of the discharge coefficient when the aperture beneath the sidewall reaches the same order of magnitude as the inlet to the plenum.

There is no direct evidence of positive side force being developed by the annular jet type of GEM. It is possible that this occurs in some degree at very low heights because of the partial resemblance to a plenum chamber. If this is so, by the same token the side force will be limited to $\chi_\phi = 0.2$ by the conditions of discharge between the ground and the machine and will not exceed this unless special features are incorporated to promote the lateral discharge.

SIMPLE THEORY

In the simple theory of the free-flying GEM, we disregard any forces due to sideways linear velocity or angular velocity of roll and consider the GEM as a rigid body acted on by the aerodynamic lifting forces. We assume that these adjust rapidly to the position of the GEM so that they are always uniquely related to it.

The lift forces are then replaceable by a single force acting through a fixed point on the machine and a moment about the roll axis through that point. For convenience we choose this point at the center of the base.

With the notation of Figure 1, we have

$$W\ddot{z}/g = -L\cos(\chi + \phi) - W, \qquad (1)$$

$$W\ddot{y}/g = L\sin(\chi + \phi), \qquad (2)$$

and

$$I\ddot{\phi}/g = M - Ll_w \sin\chi \quad . \qquad (3)$$

To solve for the motion we need to know how L, M, and χ are related to ϕ, z, and y. L is, of course, very strongly a function of the height, z, and scarcely, if at all, dependent upon the roll angle, ϕ; it is apparent that the increase of area between the upgoing side of the machine and the ground is compensated for by the decrease at the other side. We may therefore assume that $\ddot{z}$ is zero and that for small values of the angular displacement, L is constant and is equal to the weight, W. This is equivalent to saying that the heave motion is not coupled with the roll motion, and this is something which can be verified experimentally.

Equations 1, 2, and 3 then become

$$\ddot{z} = 0 \quad (z = \text{constant} = h), \qquad (4)$$

$$\ddot{y}/g = \chi + \phi, \qquad (5)$$

and

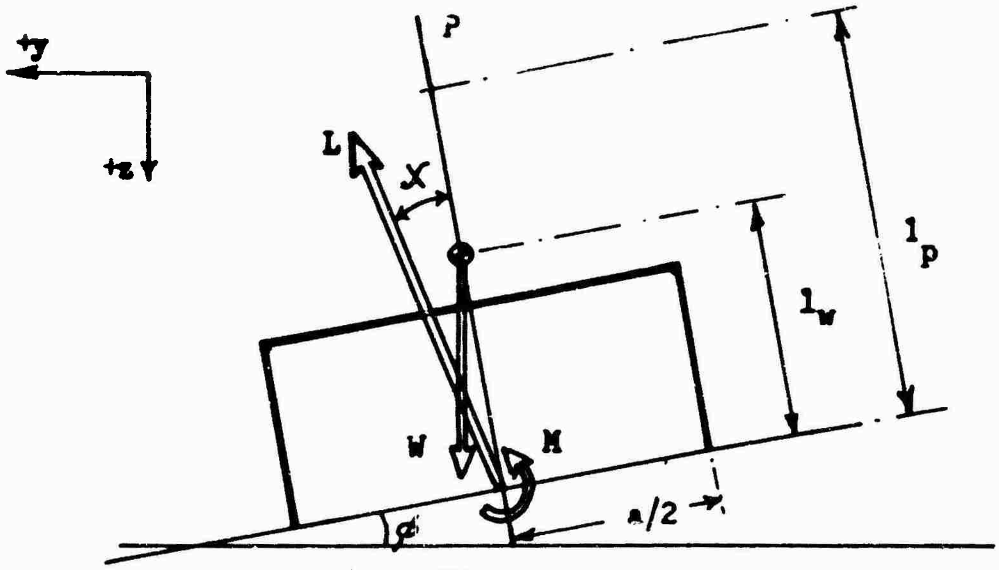
$$I/g\,\ddot{\phi} = M - Ll_w\chi. \qquad (6)$$

Equation 6 may be rewritten as

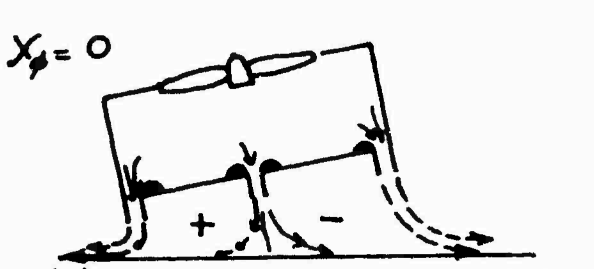
$$\ddot{\phi} = g/I \cdot (M_\phi - Ll_w\chi_\phi)\ \phi \qquad (7)$$

where the suffix ϕ denotes partial differentiation with respect to ϕ .

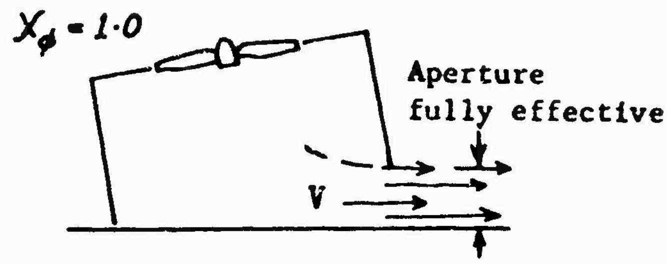
M_ϕ is the slope of the static stability curve, suitably factored, and is clearly constant over small angles of roll. If χ_ϕ is constant also,



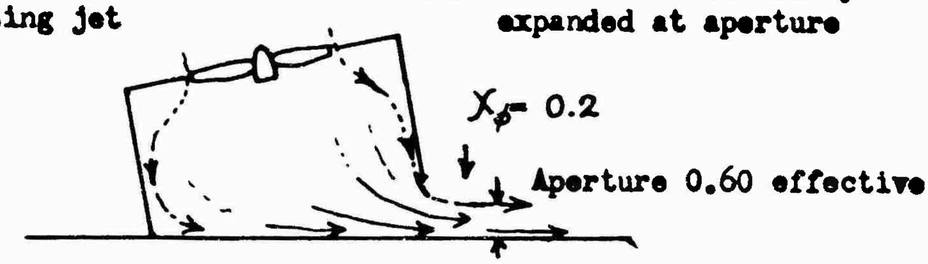
Force Diagram



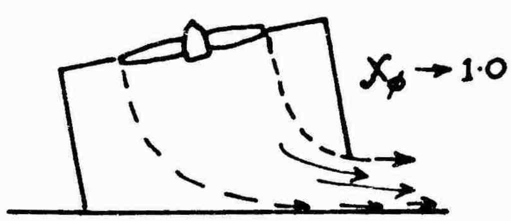
(a) Annular jet with base halved by stabilizing jet



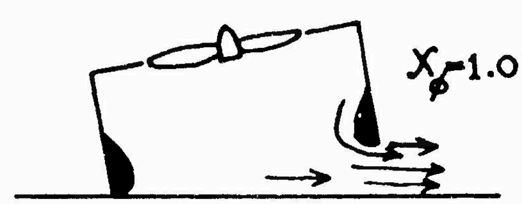
(b) Plenum with air fully expanded at aperture



(c) Plenum with discharge coefficient at aperture



(d) Plenum with appreciable velocity of flow



(e) Plenum with sidewalls afaired to give maximum lateral discharge

Figure 1. Force Diagram and Flow Models for Rolling GEM Without Damping

equation 7 may be solved to give

$$\phi = A \sin (\omega t + \alpha)$$

where

$$\omega^2 = -(M_\phi - LI_w \chi_\phi)g/I \; .$$

This represents a simple harmonic motion of angular frequency ω.

Further, from equation 5 we have

$$\ddot{y} = (\chi_\phi + 1)g.A \sin (\omega t + \alpha) \; ,$$

$$- y = (\chi_\phi + 1) \, g \, A/\omega^2 \, .\sin (\omega t + \alpha) \; ,$$

and

$$= (\chi_\phi + 1) \, g/\omega^2 \, . \, \phi \; .$$

At a point, P, located on the machine at a distance, l_p, above the base,

$$y_p = y + (l_p - l_w). \, \phi \; .$$

P is stationary if y_p is always zero, which occurs when

$$l_p - l_w = - y/\phi \; ,$$

$$= (\chi_\phi + 1) \, g/\omega^2 \; ,$$

and

$$= \frac{-(\chi_\phi + 1) \quad I}{M_\phi - LI_w \chi_\phi} \; .$$

The motion is thus a pendulous swinging about the axis through P, fixed in space and in the machine.

Case When $\chi_\phi = 0$

In the particular case when χ_ϕ is zero, as was shown in Reference 1 to be approximately true of the thin annular jet GEM,

$$l_p - l_w = -I/M\phi = g/\omega^2 . \tag{8}$$

The period of the oscillation is given by

$$\text{period} = 2\pi/\omega = 2\pi.(\overline{l_p - l_w}/g)^{\frac{1}{2}} . \tag{9}$$

This is recognizable as the period of a simple pendulum of length $l_p - l_w$. Therefore the axis, P, is located at a distance above the CG which is equal to the length of a simple pendulum of the same period.

Case When $\chi\phi = 1$

This is the theoretical case for the plenum with idealized jet discharge conditions. Here we have

$$l_p - l_w = 2g/\omega^2$$

$$= -I/(M\phi - Ll_w). \tag{10}$$

For static stability $M\phi$ is negative, and a positive value of $\chi\phi$ increases the frequency of the oscillation. The height of the axis of rotation above the CG is twice the length of the equivalent simple pendulum (from (9)).

Static and Dynamic Instability

In cases where the machine is statically unstable ($M\phi$ is positive), it will still be dynamically stable if $M\phi$ is not greater than $Ll_w\chi\phi$. In the limiting case when $M\phi$ is equal to $Ll_w\chi\phi$, the motion is aperiodic, and the GEM slides sideways without roll and fails to recover from the slightest disturbance.

Clearly, the dynamic stability is determined by the quantity $M\phi - Ll_w\chi\phi$ or, more properly, by the dimensionless form written as

$$M/La\phi - \chi\phi . l_w/a . \tag{11}$$

The dynamic stability is positive, neutral, or negative according to whether or not this quantity is negative, zero, or positive. The length, a, is some convenient measure of the size of the machine, such as the beam.

Origin of the Stabilizing Forces

Since the stability is determined by the quantities M_ϕ and χ_ϕ, it is of interest to see how these are generated.

In the case of the annular jet GEM, the jet is formed within the machine and is not primarily affected by rolling through small angles. Therefore, when the machine is at an angle, the jet on the high side is not strong enough to hold the base pressure at the increased height. The height then must fall, let us say, by an amount ΔP_b. Similarly, the jet on the low side is stronger than that required for the decreased height; thus, the base pressure must rise, say by an amount $\Delta' P_b$. If there were no stabilizing jet, this pressure gradient would create a cross flow in the cushion toward the high side. However, if the stabilizing jet is strong enough to hold the pressude difference $(\Delta + \Delta')P_b$, it will do so. This gives at once $\Delta P_b = \Delta' P_b$, in order that there shall not be an excess of lift, and a moment $\Delta M = \Delta P_b . a$. A small amount of side force will be developed to balance the partial flow of the stabilizing jet toward the high side, but otherwise the lift force will remain normal to the base.

The magnitude of the restoring moment may be estimated from a knowledge of the lift height characteristic of the machine. For the model used in these experiments, Figure 13 shows a slope of 1/0.0002 for the height against lift to the power 1.5. That is to say,

$$dh/dL = (1/0.0002) \; . \; 3/2 \; . \; L^{-2.5} \quad ,$$

$$0.5 \; d\phi/dP_b = -0.75 \; . \; 10^4 \; . \; 252^{-2.5} \quad ,$$

and

$$d\phi/dP_b = -1/68. \quad .$$

This gives

$$\frac{1}{L_a} \; . \; \frac{dM}{d\phi} = -68/252$$

$$= -0.27. \quad .$$

In the subsequent experiments, slightly lower values of the static stability were measured for the annular jet model. These are shown in Figure 16.

The simplest arrangement of a plenum chamber GEM with straight sidewalls has no obvious place where a difference of pressure between one side and the other can be maintained. Because of this, the aerodynamic moment, M, must be expected to be always small. The asymmetric flow of air across to the high side will generate side force on the machine, and this will be appreciated as a rotation of the lift vector beyond the angle of roll. The case has been discussed by Wernicke in

Reference 2. At the limiting angle when the downside is just touching the ground, the plenum is vented only at the other side (neglecting the outflow at the ends). The aperture is 2h in height and is equal to $a\phi$. If it is assumed that the air is fully expanded to atmospheric pressure at the moment when it passes the aperture and has a velocity V_h, the mass flow per unit length will be $\rho.2h.V_h$. This produces a horizontal force, $\rho.2h.V_h^2$. For the air to be fully expanded, $\rho.V_h^2 = 2P_b$. Therefore, the horizontal force is $4hP_b$, which is equal to $2\phi aPb$ or $2L\phi$. Thus, the lift is inclined at an angle 2ϕ to the ground, or at an angle ϕ to the machine. In this case $\chi = \phi$, and $\chi_\phi = 1.0$.

In practice, as borne out by the experiments with the plenum model GEM, the value $\chi_\phi = 1.0$ is not ordinarily attained. The flow picture as sketched in Figure 1b is incorrect. The discharge from the plenum will be horizontal along the surface of the ground, but at the upper boundary of the aperture there must be some flow downward and parallel to the side wall. The case approximates that of an orifice in a flat plate which is symmetrical about the ground line and for which a discharge coefficient of less than unity is appropriate. Reference 3 quotes a value C = 0.6 for two-dimensional flow through a sharp-edged orifice. With this value, the horizontal force works out to be only $1.2L\phi$ so that the side force is only $0.2L\phi$ and $\chi_\phi = 0.2$. This value is more typical of the experimental results.

In particular cases, appreciably higher values of χ_ϕ are to be expected. When the rise height is increased, the area of outlet beneath the skirt of a plenum chamber GEM becomes larger. The velocity, V_h, at the outlet is comparatively low, and as it approaches the value of the intake velocity, the plenum chamber is functioning less as a plenum and more as a duct. The tendency then is for a velocity to be maintained through the central parts of the chamber with eddies filling the corners. With these conditions, the entry conditions to the aperture are much improved and a discharge coefficient higher than 0.6 is to be expected. We would, therefore, expect χ_ϕ to increase towards unity as the hover height is increased. Such was in fact found to be the case.

In a special case where the side walls are faired to give a horizontal flow past the lower edge, the discharge coefficient may approach unity. In this case, the full value of $\chi_\phi = 1.0$ will be realized. Other effects will also be introduced, because curving the flow around the fairing will reduce the pressure on it and produce a downward force which is in opposition to the lift of the machine. As the lower side comes near to the ground the flow is cut off, and on the other side the downward force on the fairing is unbalanced and contributes a powerful stabilizing moment to right the machine. We should therefore expect this arrangement to be deficient in lift, to be statically stable with a nonlinear relationship between M and ϕ, and to have $\chi_\phi = 1.0$, thus giving a strong dynamic stability. These characteristics were noticeably present in the modified plenum model which had such a fairing.

THE MODEL GEM AND THE EXPERIMENTAL PROCEDURE

The model GEM had been built for a previous investigation[1] and required only a little modification for the present work. It is illustrated in Figures 2 and 3 in the forms used. Figure 2 shows the overall dimensions applicable to all versions and the base used in the thick annular jet version. The sectional view of Figure 2, Sheet 3, shows the annular jet in greater detail. Figure 3 shows the same thing with the base removed to provide the plenum chamber in its primary form with straight sidewalls and in the modified form with the fairings added to the sidewalls.

The "Thick" Annular Jet Model

This is so called to distinguish it from the earlier version. The annular jet is 1.00 centimeters wide and is parallel to the sidewalls. The base is quartered by stabilizing jets, which are 0.32 cm. wide. The total area of stabilizing jet is 0.152 times the area of the annular jet. This is sufficient to make the machine statically stable, though not strongly so.

For changing the position of the center of gravity, the machine is provided with two ballast weights of 32 grams each. These are placed at the ends of the yardarms to give the low position and at the masthead to give the high position. The extra high position is achieved by an additional weight at the masthead, which increases the allover weight of the machine considerably.

The model is powered by two small permanent magnet direct-current motors connected in series across a 36-volt supply with a rheostat to adjust the current. The assumption is made that the power delivered to the fans is determined by the current in the circuit. The fans are mounted in faired entries to the body of the machine, but no special provision is made for distributing the air evenly to the periphery.

The machine is equipped with a superstructure which provides roll pivot axes at various heights.

The Plenum Chamber Model

This is derived from the annular jet model simply by removal of the base, which reduces the allover weight somewhat but leaves the other particulars unaltered. For the "modified" plenum, the addition of the small fairings at the lower edges of the walls increases the weight by a small amount.

Particulars of both versions of the model are given in Table 1.

Dimensions in Centimeters

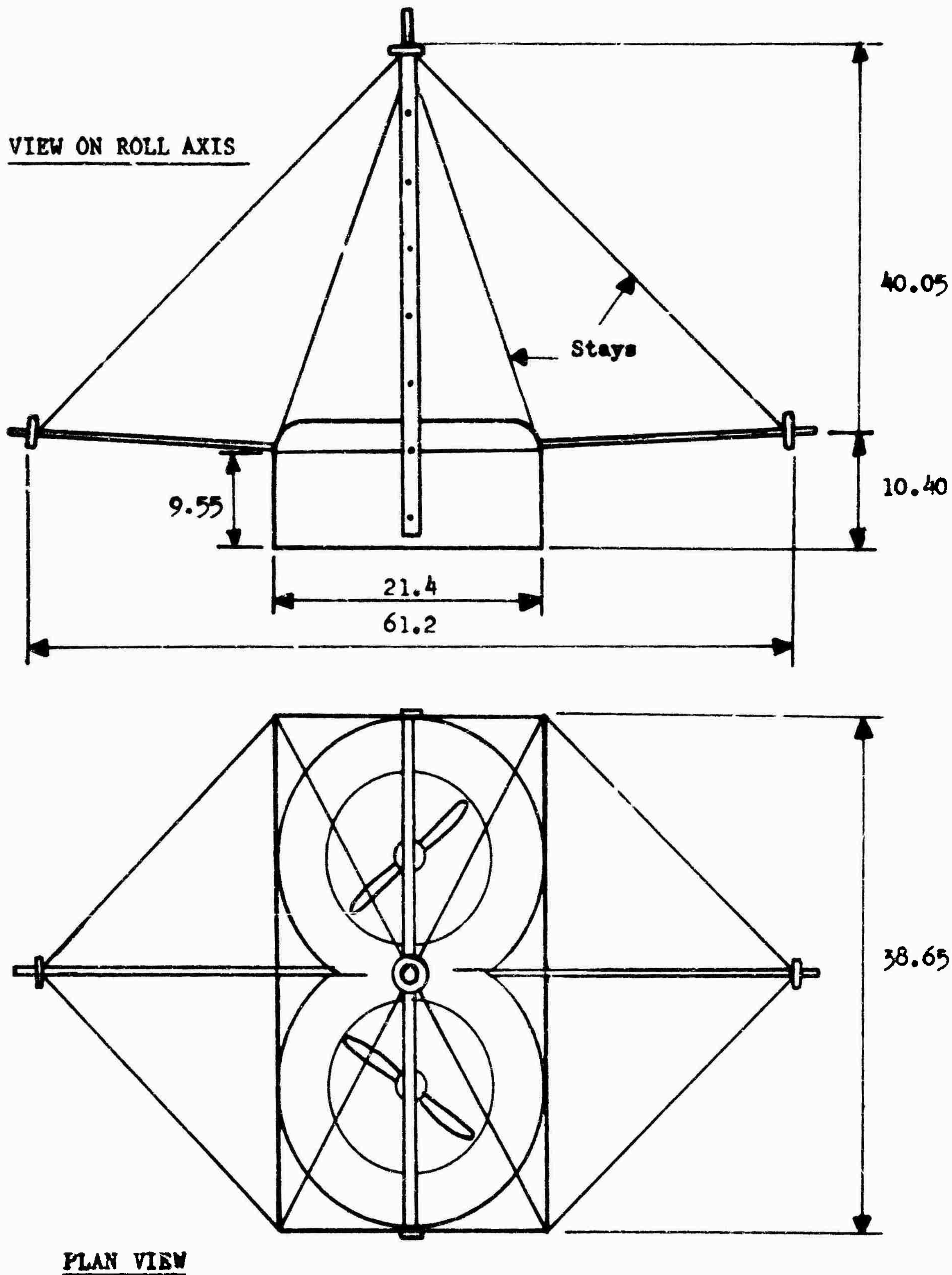
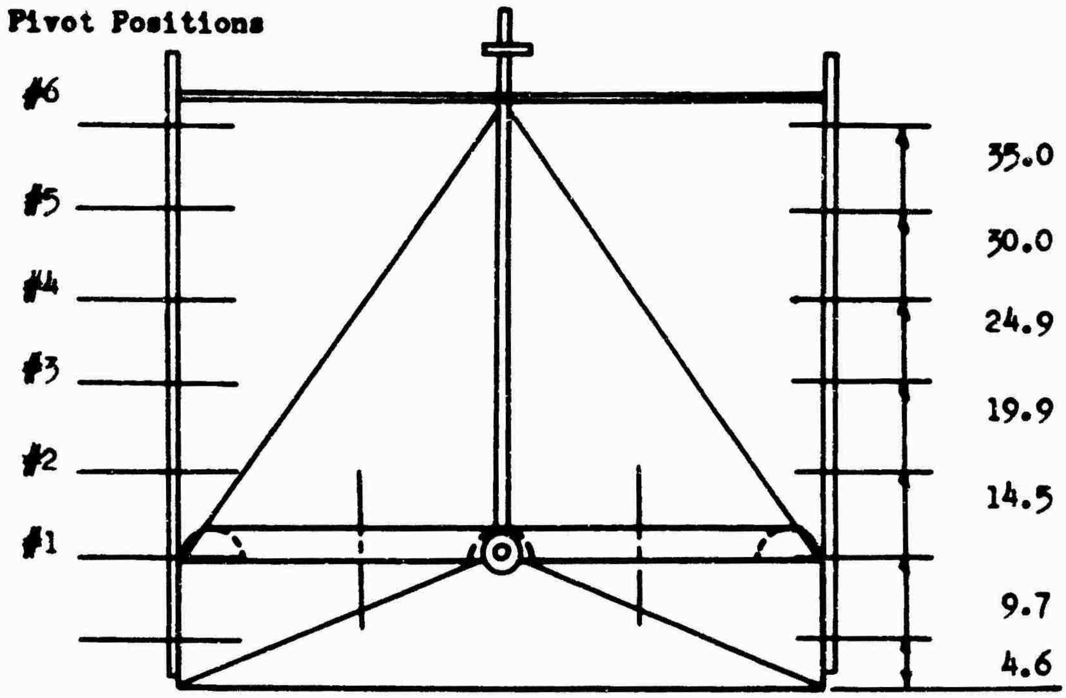
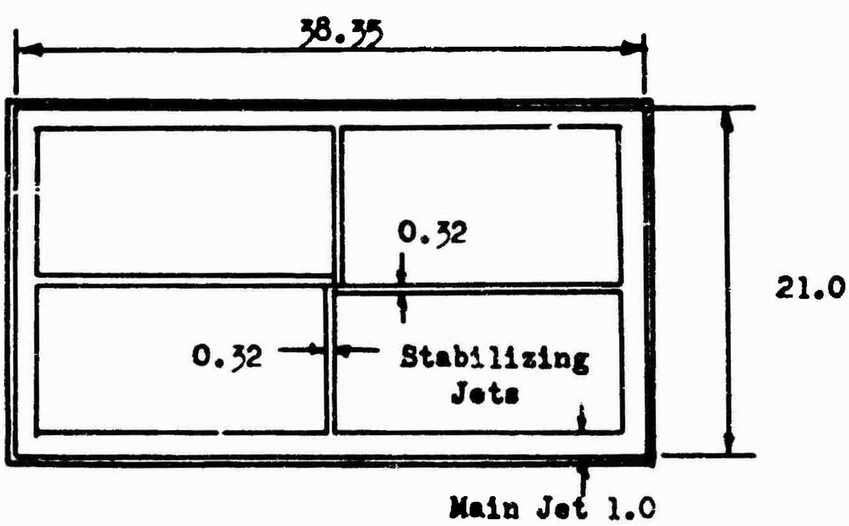


Figure 2, Sheet 1. The GEM Model

Dimensions in Centimeters

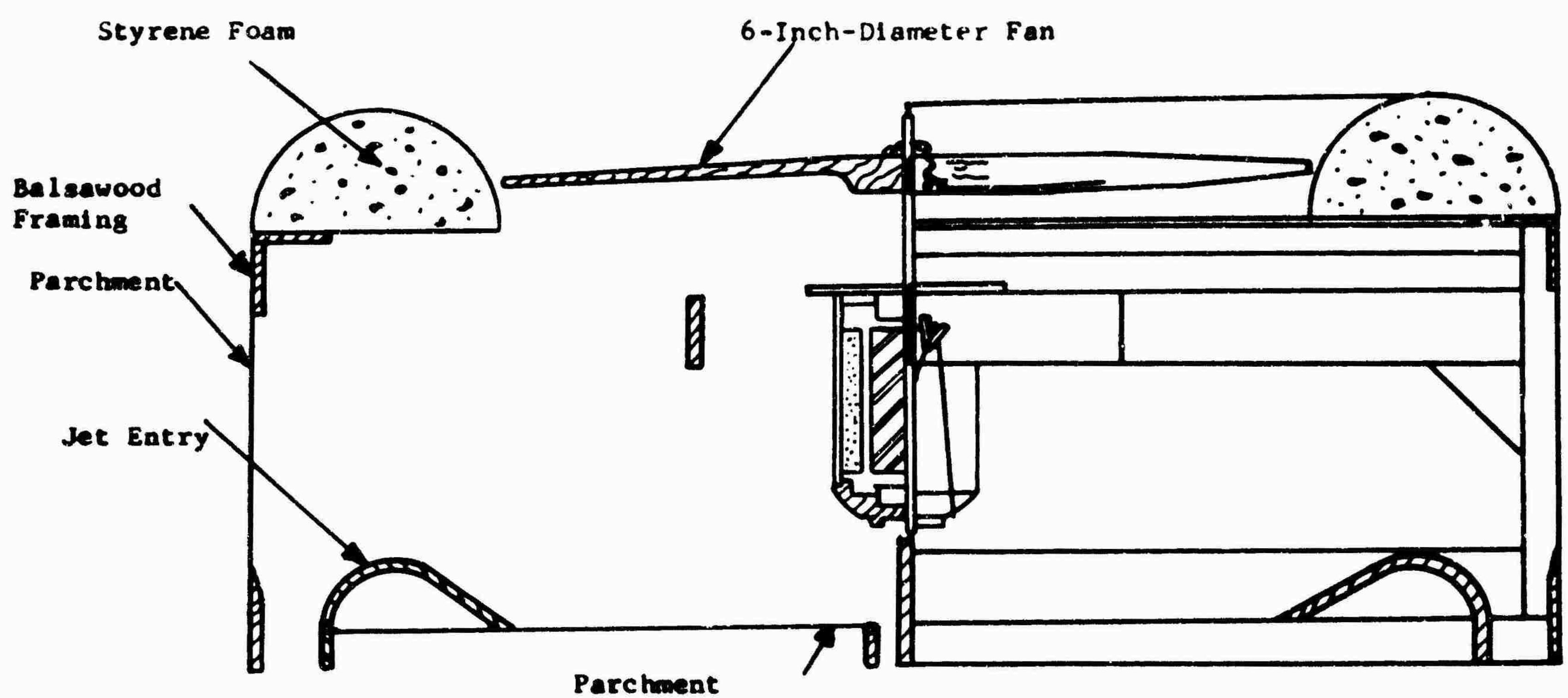


SIDE VIEW



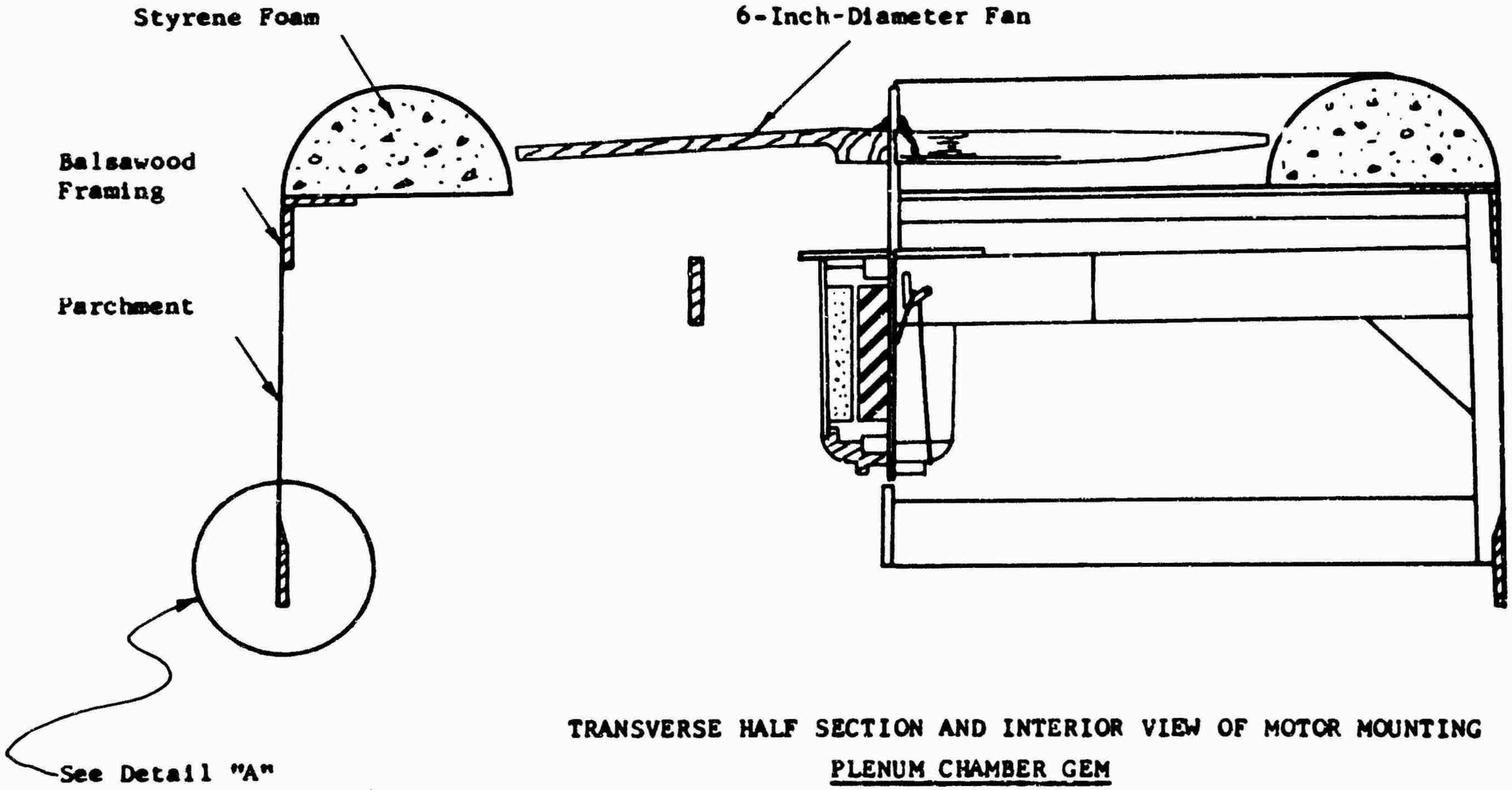
VIEW ON BASE OF ANNULAR JET MODEL

Figure 2, Sheet 2. The GEM Model



TRANSVERSE HALF SECTION AND INTERNAL VIEW OF MOTOR MOUNTING - ANNULAR JET GEM

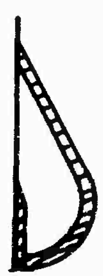
Figure 2, Sheet 3. The GEM Model



TRANSVERSE HALF SECTION AND INTERIOR VIEW OF MOTOR MOUNTING

<u>PLENUM CHAMBER GEM</u>

(also showing modification at detail "A")



DETAIL "A"

Plenum Sidewall With Fairing Added To Produce
Maximum Lateral Discharge

Figure 3. The Two Versions of the Plenum Chamber GEM Model

TABLE 1

MODEL DIMENSIONS AND TEST DATA

Plenum Model

	Tare	Low CG	High CG	Extra High CG
Weight in grams	210.4	274.6	274.6	380.0
Moment of Inertia about CG, grams.cm.^{2}	21,000	81,000	68,000	111,000
CG height above base, cm.	9.15	9.50	16.35	22.9

Annular Jet Model

	Tare	Low CG	High CG	Extra High CG
Weight in grams	252.4	316.6	316.6	420.0
Moment of Inertia about CG, grams.cm.^{2}	28,200	88,500	78,000	150,000
CG height above base, cm.	8.85	9.05	15.1	21.8

Annular Jet Width 1.0cm. Stabilizing Jet Width 0.32cm.
Ratio, Stabilizing Jet Area / Annular Jet Area 0.152

Dimensions Common to Both Models

Length of Model at Base, inside faces of end walls	38.35cm.
Beam of Model at Base, inside faces of side walls	21.0 cm.
Area of Base	805.4 cm.^{2}
Fans, 2-x-6-inch diameter, Disc Area	365cm.^{2}
Power available, approximately	30 watts

Test Altitudes	0.70cm.,	1.00cm.,	1.45cm.,	1.90cm.
Altitude Ratio h/a	0.033	0.048	0.069	0.091

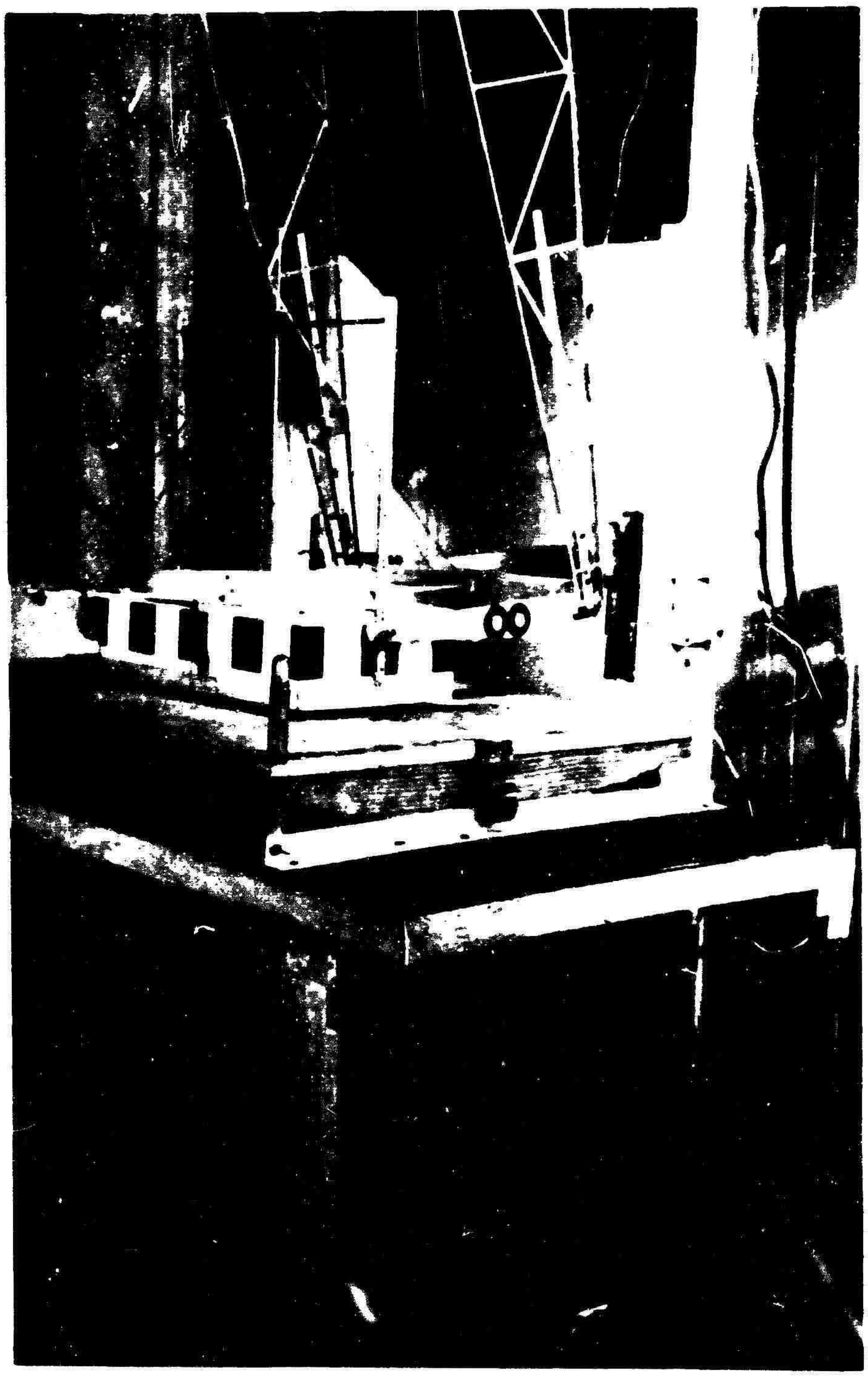


Figure 4. The Test Rig Set Up to Measure Lift

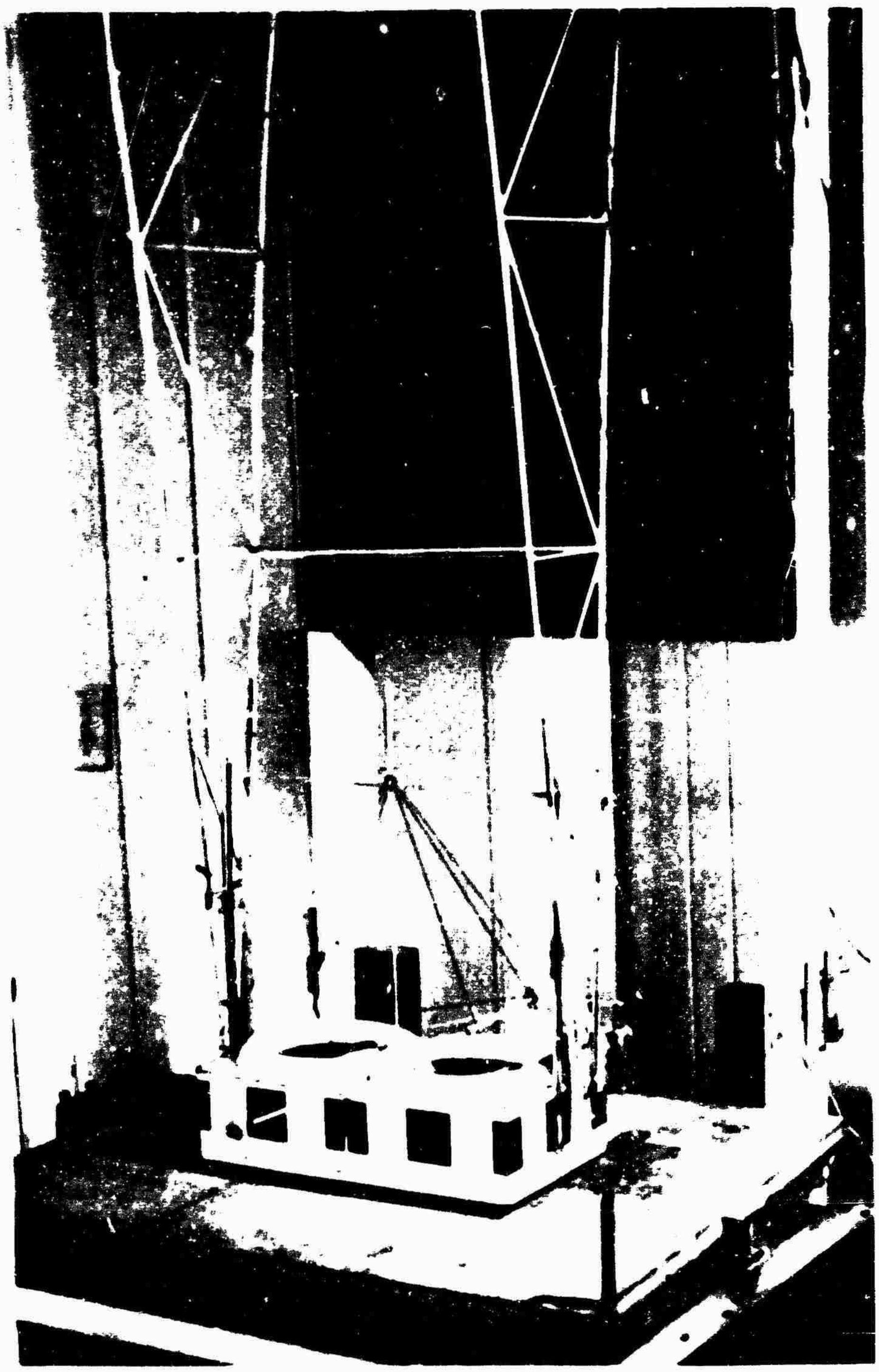


Figure 5. The GEM Model in the Trapeze Rig

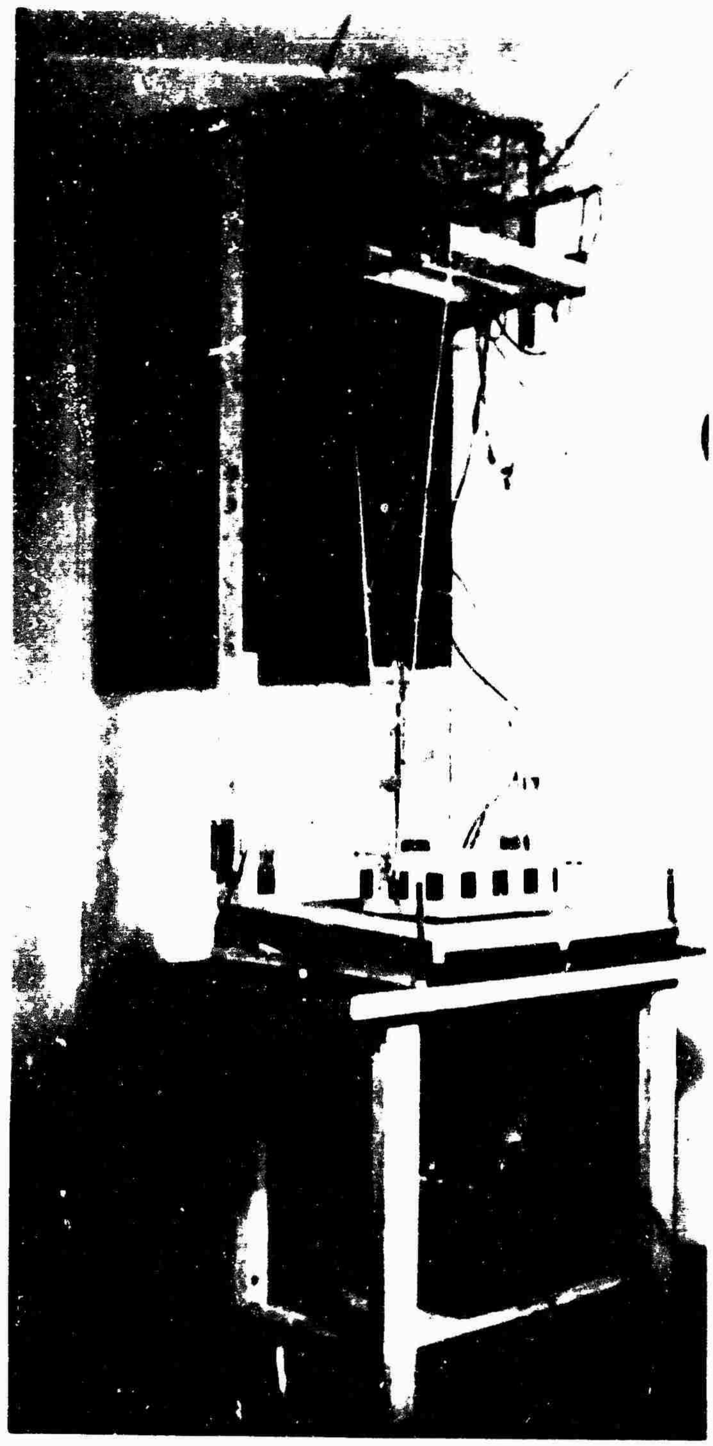


Figure 6. The Test Stand

Figure 7.   The GEM Model Showing the Base and Jet Configuration

Measurement of Lift

For this the ballast weights were removed. A pivot axis slightly above the CG was selected and used to support the model in the arms of a horizontal weigh beam. The beam was pivoted to allow the machine to rise and fall vertically and was provided with a counterbalance so that the vertical force on the machine could be varied and measured.

The rise height of the machine was derived from the angular position of the weigh beam as indicated by the position of a spot of light reflected from a small mirror attached to it.

In the power-off condition, the machine rested on the horizontal ground board. When the power was applied, the lift force was predetermined by the balance of the weigh beam and the machine rose to the appropriate height in accordance with the power value. Results of these tests are given in Figure 8 with the variation of rise height with current for fixed values of the lift, the plenum chamber model, and the modified plenum chamber model. Figure 9 gives similar data for the annular jet GEM. The data are replotted as a variation of lift with rise height for fixed values of the current in Figures 10 and 11. From these graphs the lift can be determined for any given values of the rise height and current. The numerical data are given in Table 2.

Measurement of the Static Stability in Roll

For this measurement the machine remained pivoted in the horizontal weigh beam, which was now clamped so as to restrain the machine to a fixed height. Rolling moments were applied by placing a small weight at positions along the yardarm. This caused the machine to adopt angular positions, which were observed by the reflection from a small mirror attached to it. These r sults are plotted in Figures 12 through 15 as the ratio M/La against the angle of roll for various values of the rise height. Lift was derived from motor current using the calibration of the preceding section. Because of the zero dimensions of the parameter, M/La, the values at different values of the lift plot along the same lines.

For the annular jet GEM, the slopes of the graphs show little change throughout the range of rise height. This indicates that the machine is consistently stable with little change of stiffness in the range.

The plenum GEM is only very slightly stable at the lower heights in the range and is neutrally stable at the higher end of the range.

The modified plenum is strongly stable at the height at which it was tested, roughly in the middle of the range.

The numbers are given in Tables 3 and 4. Figure 16 shows the stiffness of the annular jet GEM in comparison with the values previously obtained for the thin annular jet in Reference 1, related to theoretical estimates.

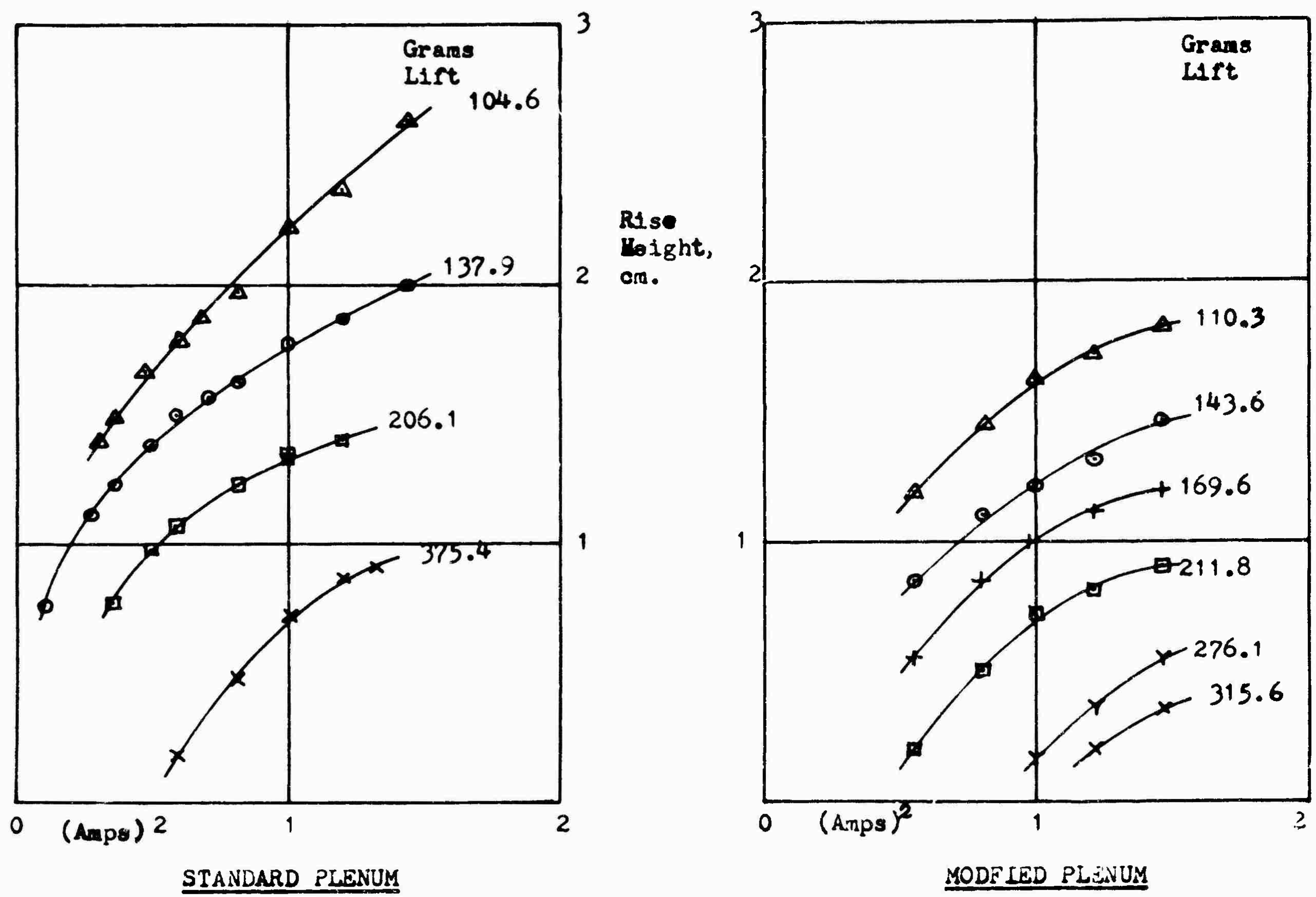


Figure 8. Variation of Rise Height with Motor Current for Fixed Values of Lift Plenum Chamber GEMS

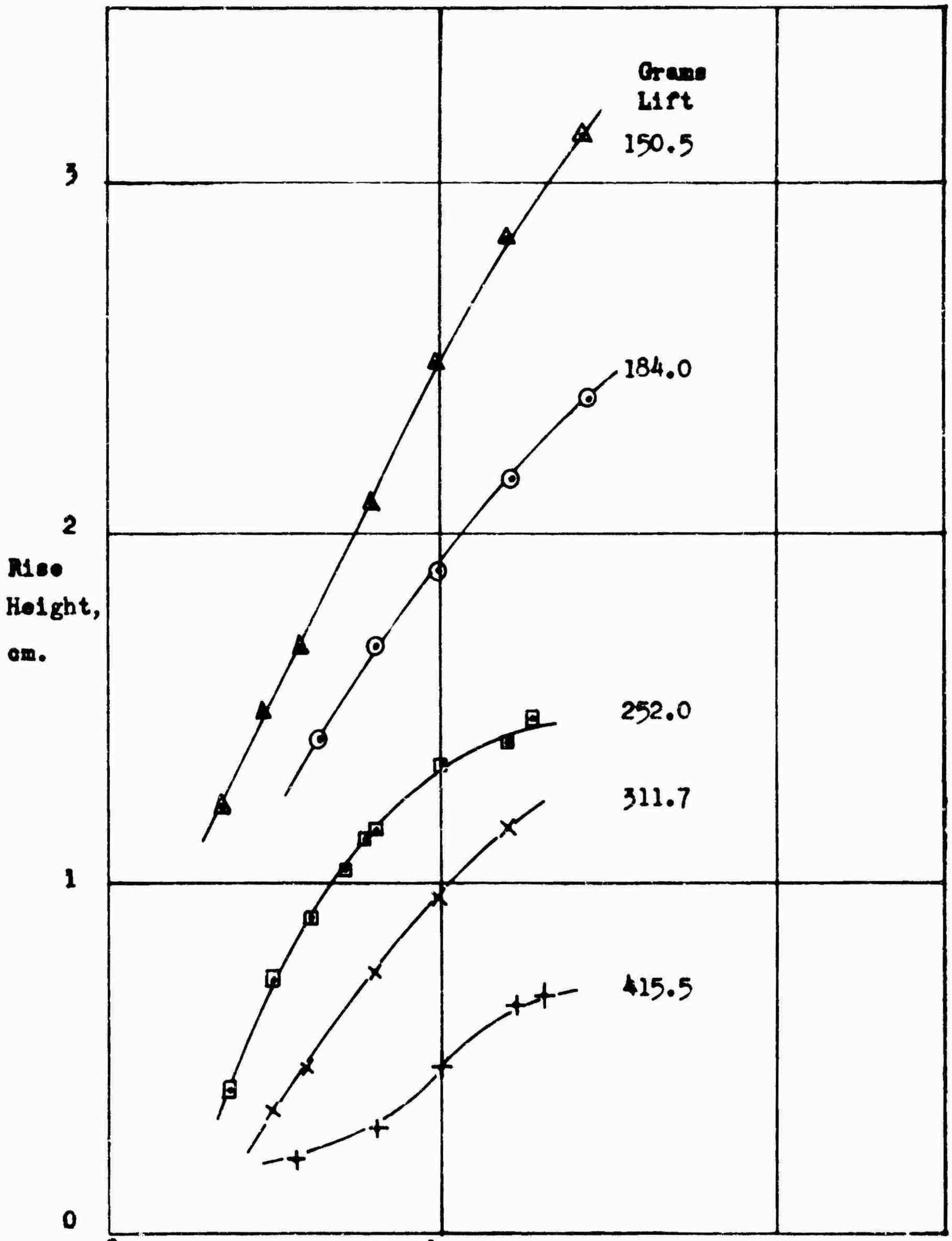
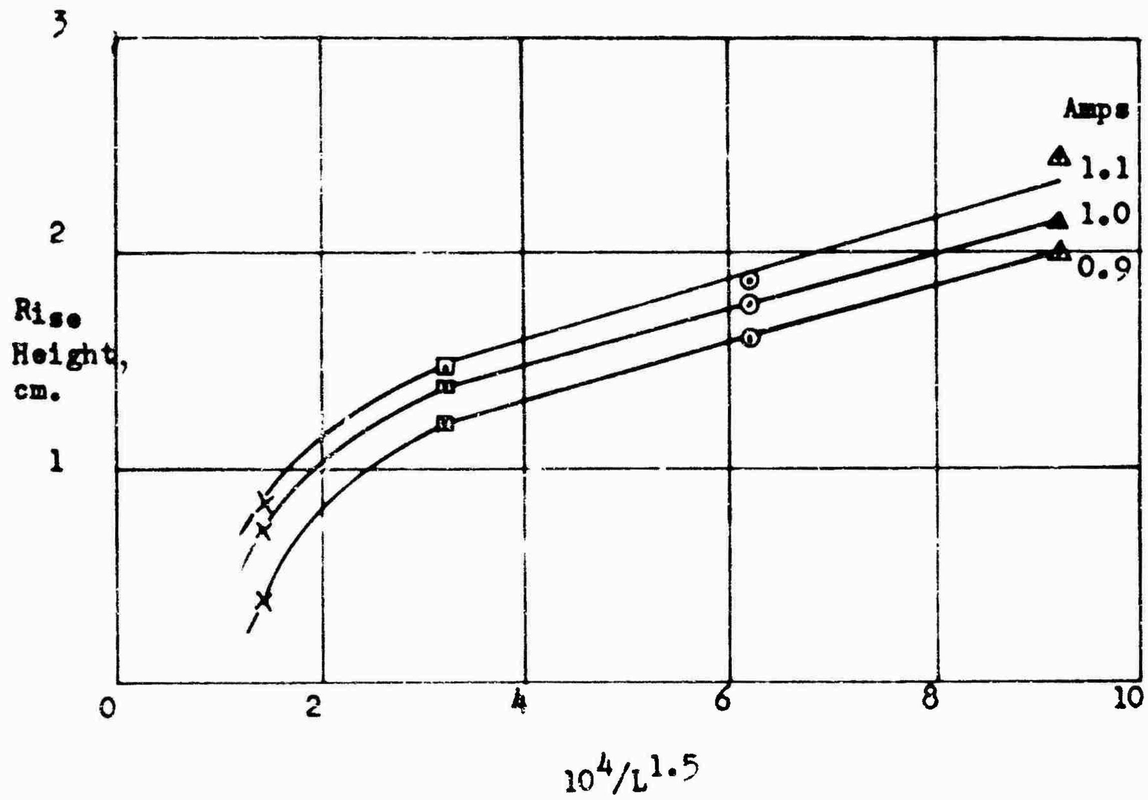
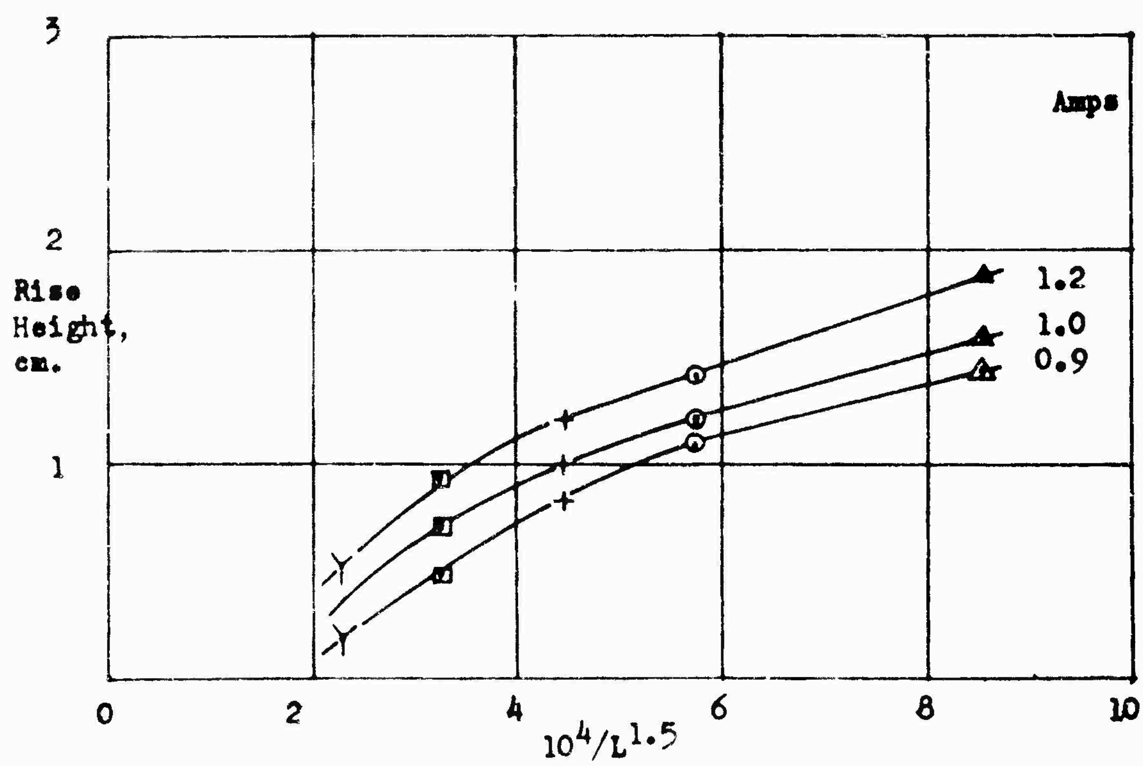


Figure 9. Variation of Rise Height With Motor Current for Fixed Values of Lift - Thick Annular Jet Model GEM



STANDARD PLENUM



MODIFIED PLENUM

Figure 10. Variation of Lift With Rise Height for Fixed Motor Currents - Plenum Chamber GEMs

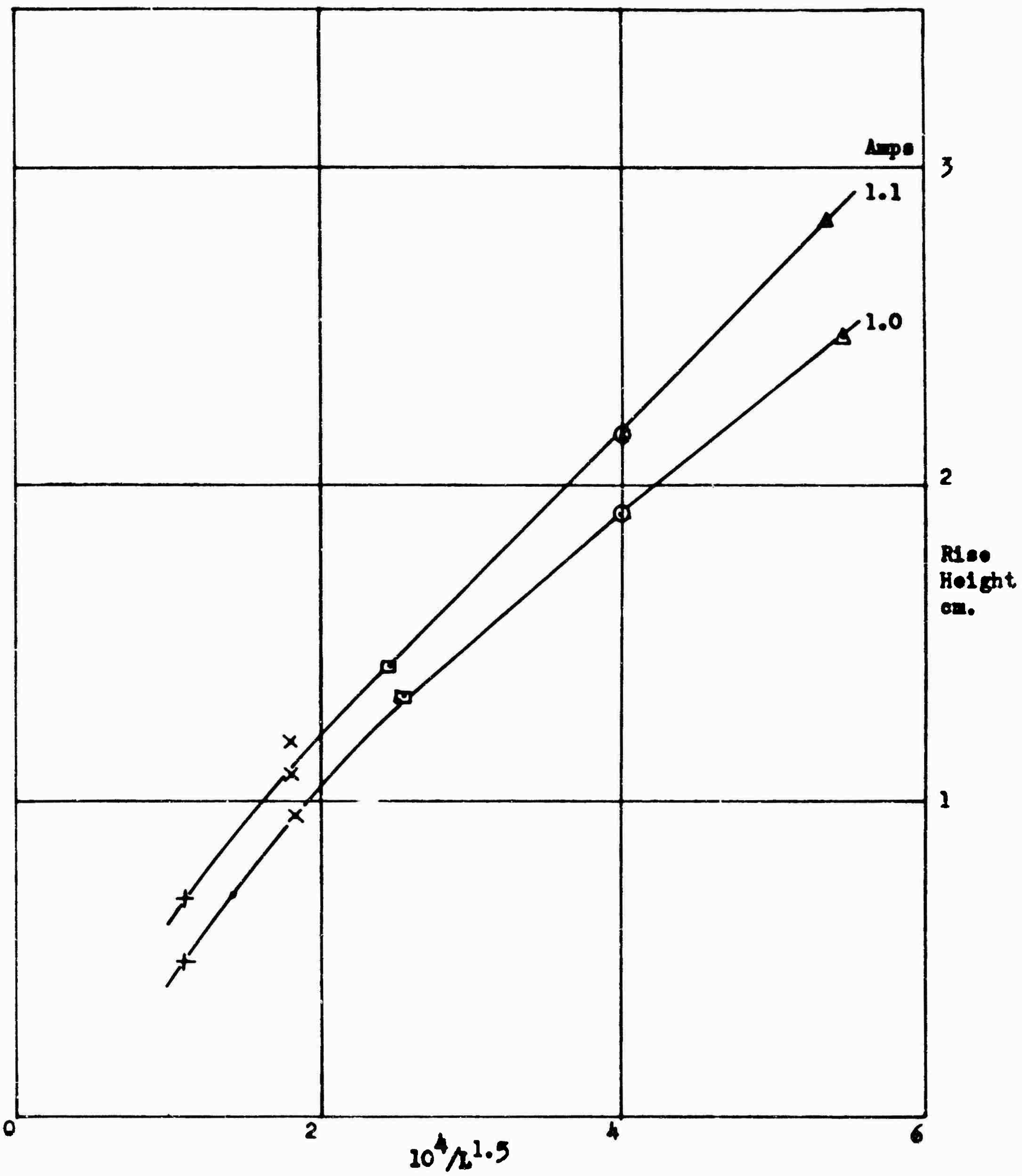


Figure 11. Variation of Lift With Rise Height for Fixed Motor Currents - Thick Annular Jet Model Gem

TABLE 2

VARIATION OF RISE HEIGHT WITH MOTOR CURRENT FOR FIXED LIFTS

ANNULAR JET GEM

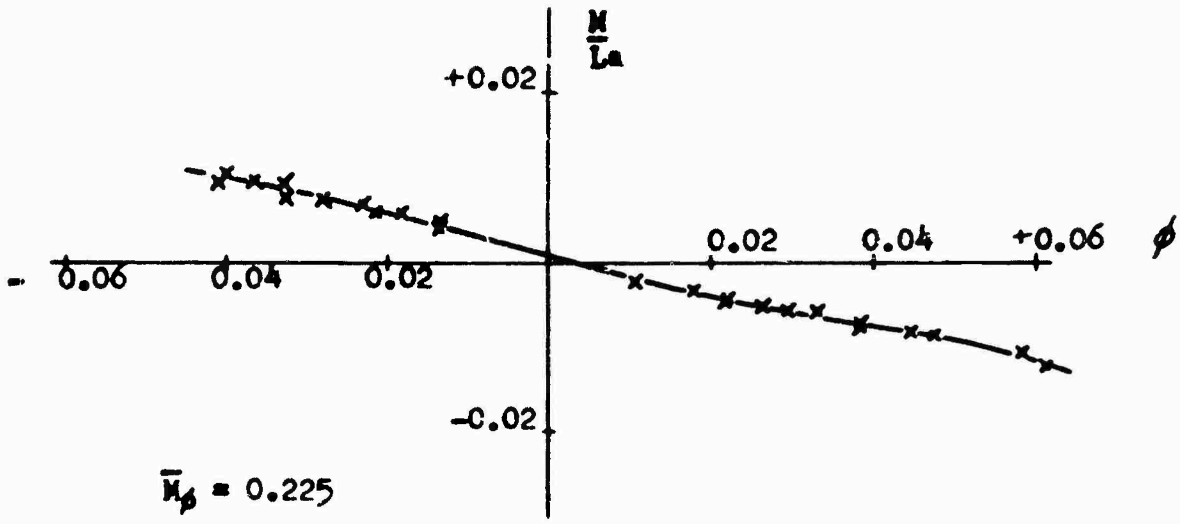
Lift	Current	Height
415.5	1.15	0.665
	1.10	0.665
	1.00	0.492
	0.90	0.308
	0.73	0.246
311.7	1.10	1.106
	1.00	0.96
	0.90	0.763
	0.77	0.492
	0.70	0.357
252.0	1.15	1.51
	1.10	1.41
	1.00	1.27
	0.90	1.12
	0.80	0.897
	0.70	0.652
	0.60	0.394
184.0	1.20	2.38
	.10	2.14
	1.00	1.89
	0.90	1.65
	0.81	1.40
150.5	1.20	3.13
	1.10	2.83
	1.00	2.47
	0.90	2.09
	0.77	1.66
	0.70	1.49
	0.60	1.22

PLENUM GEM

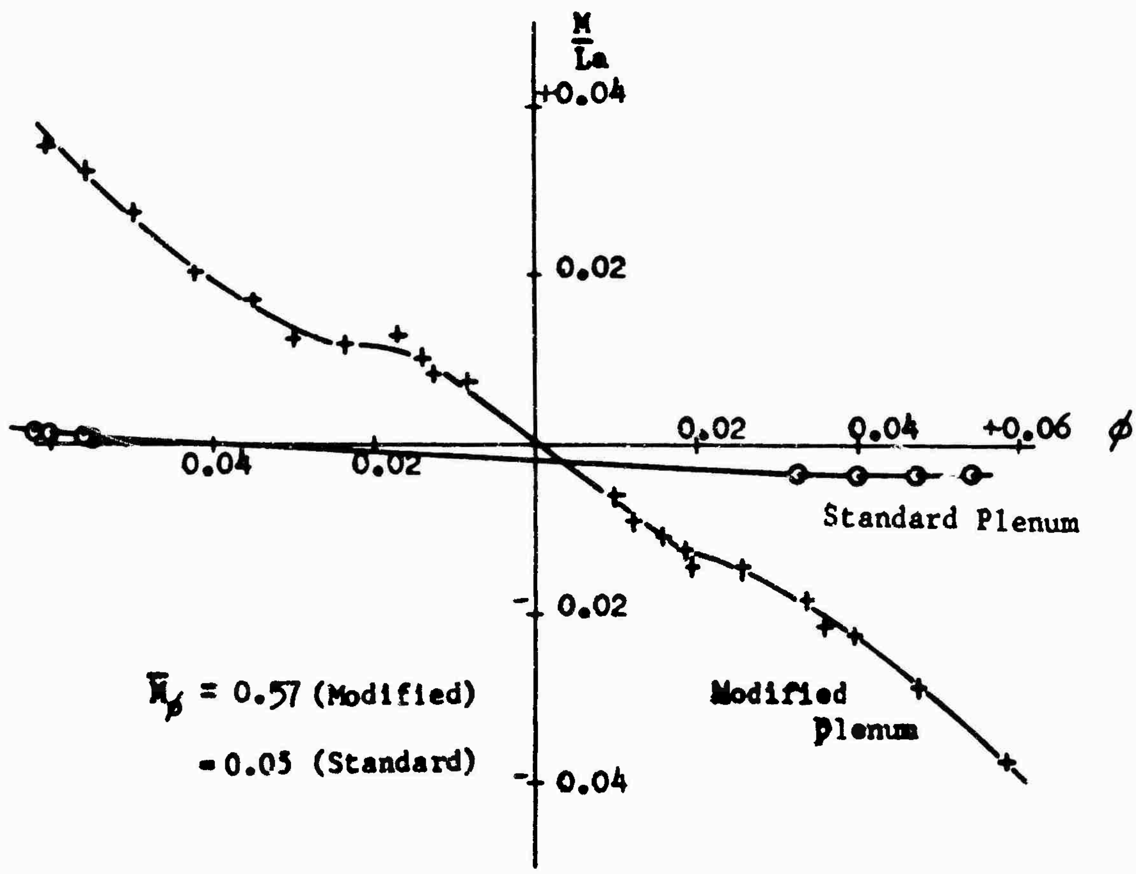
Lift	Current	Height
375.4	0.77	0.184
	0.90	0.480
	1.00	0.774
	1.10	0.872
	1.15	0.885
206.1	0.60	0.783
	0.70	0.985
	0.77	1.046
	0.90	1.215
	1.00	1.350
	1.10	1.390
137.9	0.55	1.13
	0.60	1.23
	0.70	1.38
	0.76	1.50
	0.84	1.57
	0.90	1.64
	1.00	1.76
	1.00	1.77
	1.10	1.87
	1.20	1.99
104.6	0.55	1.40
	0.60	1.50
	0.70	1.65
	0.82	1.88
	0.90	1.99
	1.00	2.24
	1.00	2.12
	1.10	2.36
	1.20	2.62

MODIFIED PLENUM GEM

Lift	Current	Height
315.5	1.10	0.19
	1.20	0.35
276.1	1.00	0.175
	1.10	0.364
	1.20	0.553
211.8	0.75	0.270
	0.80	0.364
	0.90	0.486
	1.00	0.675
	1.10	0.783
	1.20	0.917
169.6	0.75	0.54
	0.80	0.675
	0.90	0.85
	1.00	0.985
	1.10	1.092
	1.20	1.21
143.6	0.75	0.837
	0.80	0.945
	0.90	1.08
	1.00	1.19
	1.10	1.32
	1.20	1.44
111.8	0.75	1.19
	0.80	1.28
	0.90	1.46
	1.00	1.58
	1.10	1.70
	1.20	1.86

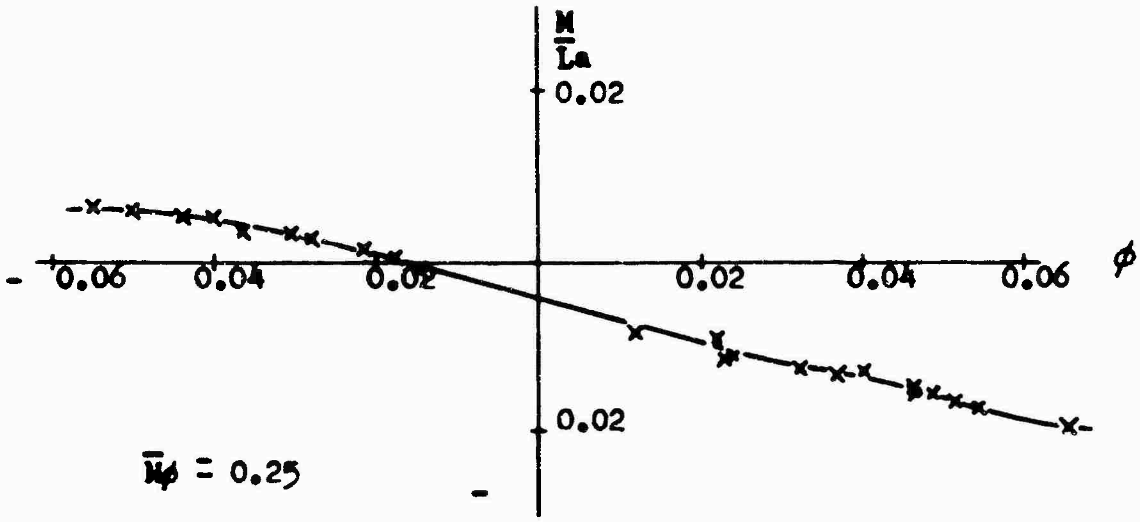


ANNULAR JET MODEL GEM

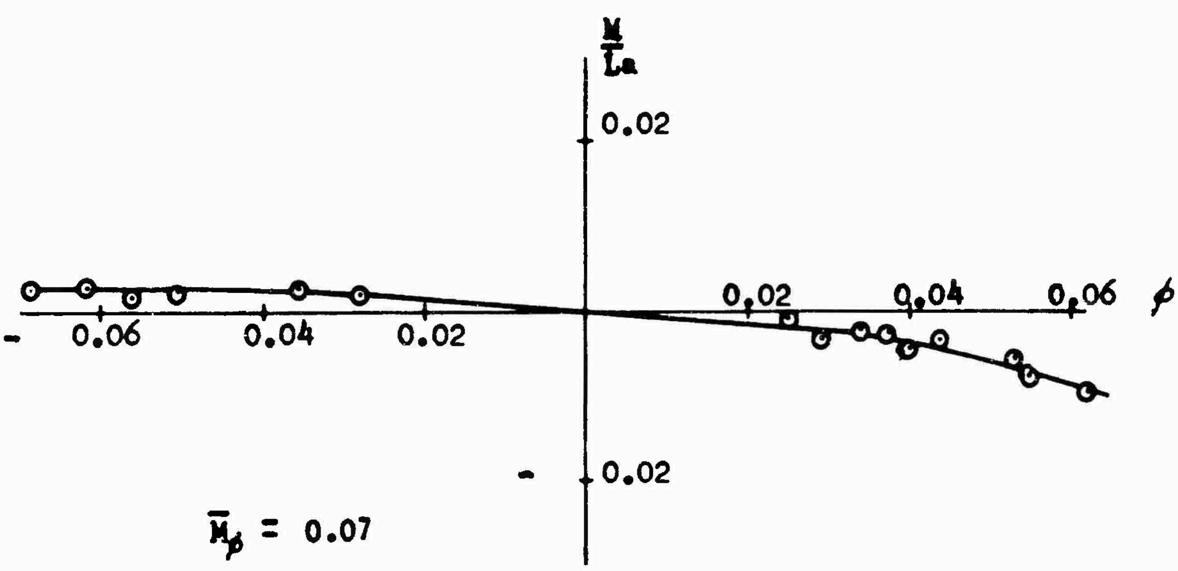


PLENUM AND MODIFIED PLENUM MODEL GEMS

Figure 12. Static Stability in Roll at h = 0.70cm. (h/a = 0.033)

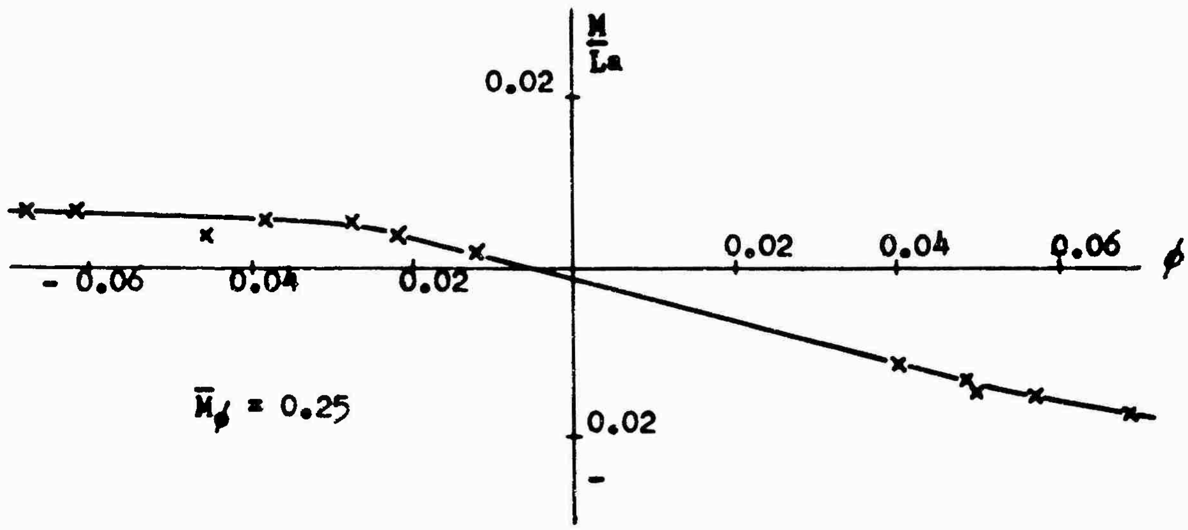


ANNULAR JET MODEL GEM

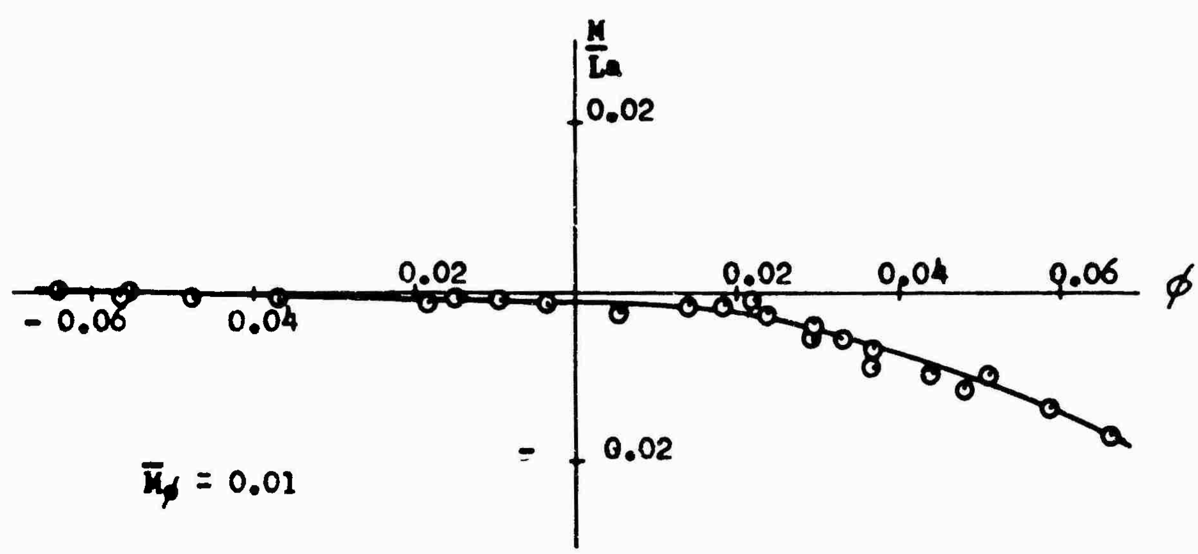


PLENUM MODEL GEM

Figure 13. Static Stability in Roll at h = 1.00cm. (h/a = 0.048)

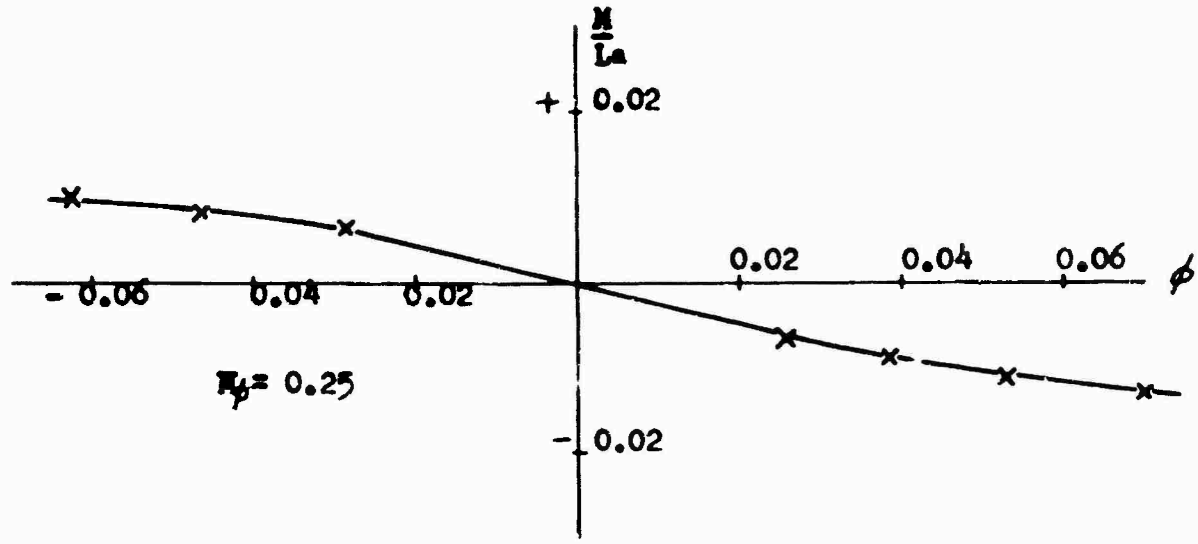


ANNULAR JET MODEL GEM

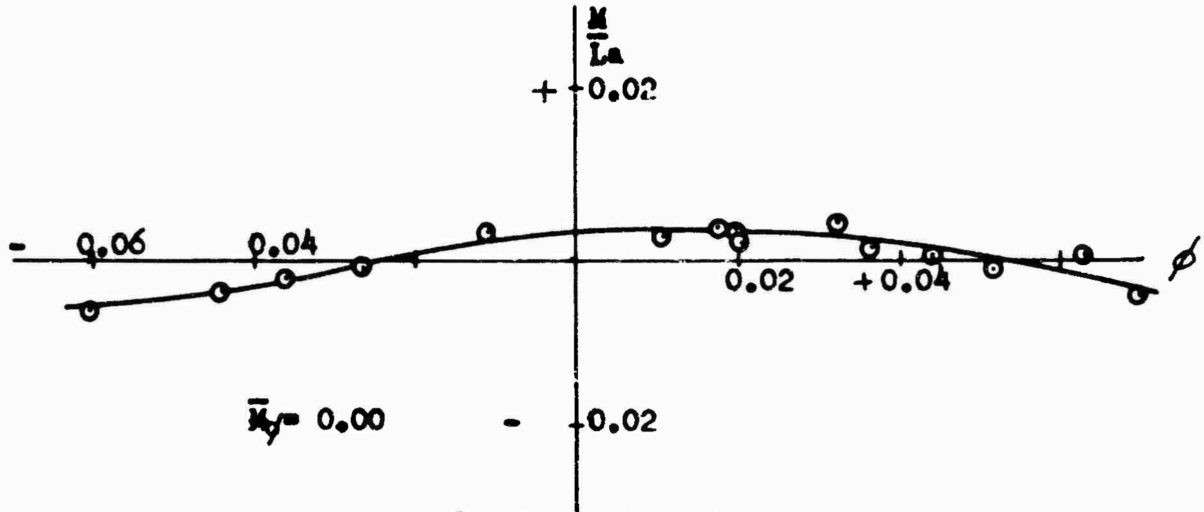


PLENUM MODEL GEM

Figure 14. Static Stability in Roll at h = 1.45cm. (h/a = 0.069)



ANNULAR JET MODEL GEM



PLENUM MODEL GEM

Figure 15. Static Stability in Roll at h = 1.90cm. (h/a = 0.091)

TABLE 3

STATIC STABILITY IN ROLL - ANNULAR JET GEM

Lift = 362 grams h = 0.70cm		Lift = 300 grams h = 1.00cm		Lift = 266 grams h = 1.45cm		Lift = 182 grams h = 1.90cm	
M/La	tan ∅	M/La	tan ∅	M/La	tan ∅	M/La	tan ∅
+0.0116	-0.0728	+0.0078	-0.0730	+0.0090	-0.0751	+0.0136	-0.0940
0.0115	0.0692	0.0066	0.0547	0.0068	0.0611	0.0127	0.0758
0.0097	0.0415	0.0058	0.0496	0.0067	0.0678	0.0104	0.0626
0.0107	0.0401	0.0055	0.0438	0.0059	0.0385	0.0084	0.0465
0.0095	0.0364	0.0050	0.0401	0.0054	0.0274	0.0063	0.0282
0.0091	0.0328	0.0032	0.0365	0.0036	0.0458	-0.0066	+0.0256
0.0075	0.0328	0.0031	0.0306	0.0035	0.0216	0.0082	0.0384
0.0073	0.0280	0.0026	0.0270	0.0018	0.0117	0.0108	0.0523
0.0069	0.0229	0.0015	0.0215	-0.0001	+0.0282	0.0129	0.0700
0.0056	0.0218	0.0013	0.0219	0.0113	0.0402	0.0138	0.0867
0.0059	0.0182	0.0003	0.0175	0.0133	0.0487	0.0173	0.1094
0.0050	0.0138	-0.0010	0.0149	0.0148	0.0494		
0.0038	0.0138	0.0084	+0.0116	0.0152	0.0567		
-0.0024	+0.0102	0.0097	0.0212	0.0170	0.0678		
0.0033	0.0178	0.0109	0.0233				
0.0041	0.0218	0.0112	0.0230				
0.0043	0.0218	0.0123	0.0321				
0.0053	0.0262	0.0130	0.0401				
0.0057	0.0291	0.0133	0.0365				
0.0059	0.0328	0.0151	0.0474				
0.0079	0.0383	0.0158	0.0482				
0.0073	0.0383	0.0163	0.0511				
0.0081	0.0447	0.0173	0.0547				
0.0089	0.0473	0.0192	0.0657				
0.0106	0.0583	0.0195	0.0683				
0.0102	0.0601						

TABLE 4

STATIC STABILITY IN ROLL - PLENUM CHAMBER GEMs

PLENUM MODEL GEM								MODIFIED PLENUM MODEL GEM	
Lift = 380.0grams, h = 0.70 cm		Lift = 283 grams, h = 1.00 cm		Lift = 208 grams, h = 1.45 cm		Lift = 126 grams, h = 1.90 cm		Lift = 207 grams, h = 0.70 cm	
M/La	tan Ø	M/La	tan Ø	M/La	tan Ø	M/La	tan Ø	M/La	tan Ø
+0.0017	-0.0617	+0.0086	-0.0985	+0.0014	-0.0700	-0.0059	-0.0600	+0.0355	-0.0610
0.0014	0.0601	0.0058	0.0910	0.0009	0.0640	0.0034	0.0440	0.0276	0.0494
0.0012	0.0554	0.0766	0.0004	0.0004	0.0550	0.0020	0.0359	0.0202	0.0422
0.0008	0.0547	0.0042	0.0785	-0.0001	0.0565	0.0004	0.0264	0.0200	0.0386
-0.0031	+0.0328	0.0029	0.0685	0.0004	0.0478	+0.0031	0.0110	0.0172	0.0350
0.0032	0.0401	0.0030	0.0620	0.0004	0.0367	0.0027	+0.0110	0.0128	0.0300
0.0031	0.0475	0.0027	0.0510	0.0011	0.0184	0.0034	0.0176	0.0118	0.0234
0.0030	0.0547	0.0019	0.0563	0.0006	0.0147	0.0033	0.0202	0.0131	0.0170
0.0034	0.0736	0.0028	0.0357	0.0009	0.0092	0.0014	0.0206	0.0109	0.0141
0.0023	0.0758	0.0022	0.0280	0.0011	0.0037	0.0041	0.0323	0.0083	0.0123
		-0.0009	+0.0250	0.0023	+0.0055	0.0010	0.0366	0.0067	0.0083
		0.0020	0.0339	0.0016	0.0140	0.0001	0.0440	-0.0061	+0.0094
		0.0031	0.0287	0.0014	0.0184	-0.0010	0.0513	0.0089	0.0119
		0.0024	0.0372	0.0006	0.0220	+0.0006	0.0630	0.0106	0.0155
		0.0033	0.0437	0.0028	0.0239			0.0128	0.0188
		0.0043	0.0401	0.0055	0.0293			0.0143	0.0191
		0.0052	0.0530	0.0038	0.0293			0.0148	0.0263
		0.0078	0.0547	0.0051	0.0331			0.0183	0.0335
		0.0096	0.0620	0.0081	0.0367			0.0215	0.0364
				0.0067	0.0367			0.0221	0.0393
				0.0097	0.0442			0.0288	0.0473

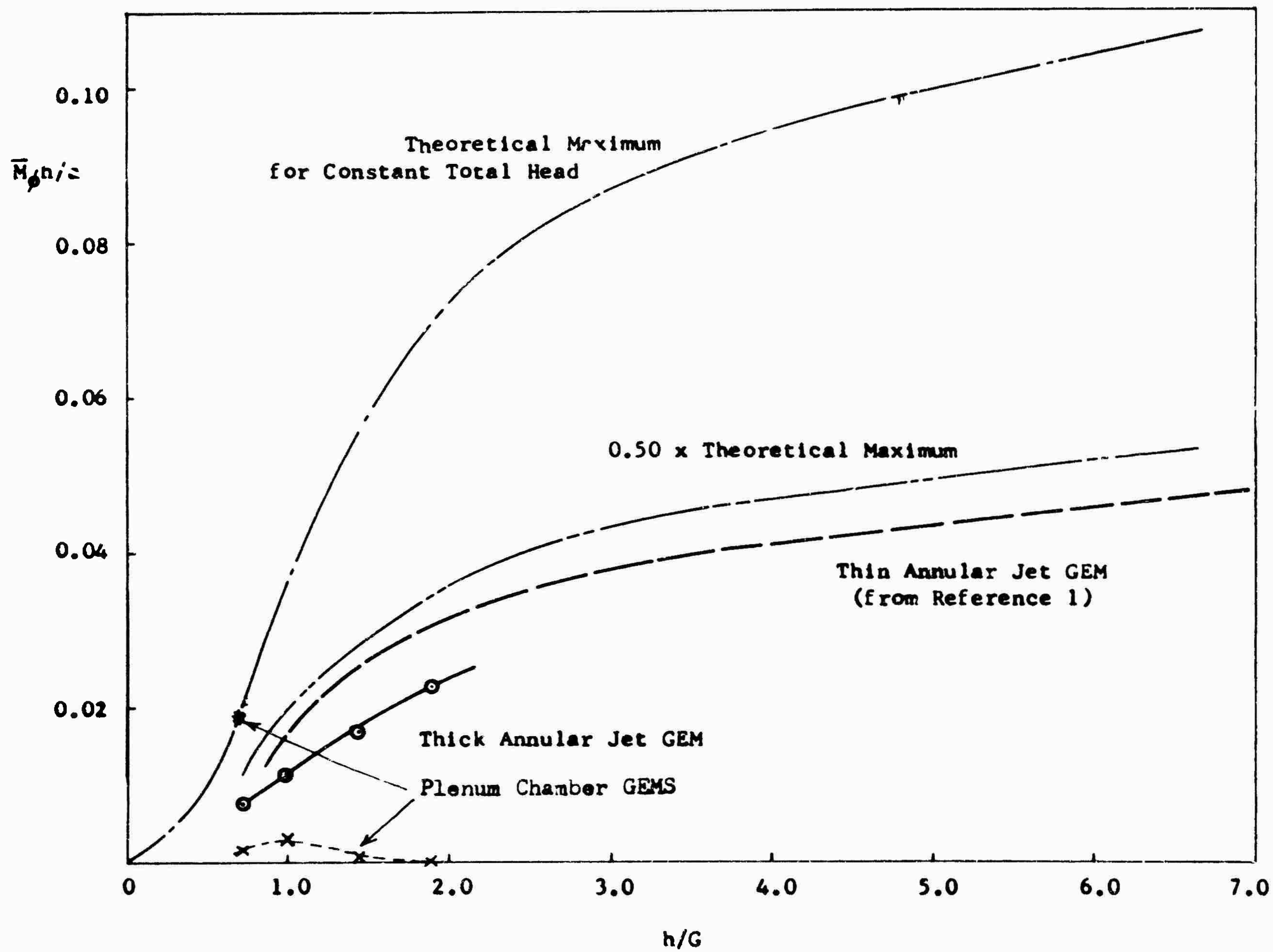


Figure 16. Variation of Static Stability With Height - Annular Jet GEMS and Plenum Chamber GEMS

Measurement of the Side Force

The side force, $L\chi$, is the component of the lift which is parallel to the base of the machine when the machine is at an angle to the ground. More particularly, it is the horizontal force on the machine when the machine if flying level over sloping ground. The side force is uphill or downhill according to whether or not χ_ϕ is positive or negative.

To measure the side force, the model was clamped in a tall "trapeze" structure which was free to swing about an axis 127.4 centimeters above the base of the mod.l. The assembly was ballasted so that it hung with the model base positioned horizontally in the static, power-off condition. The ground board was set down to give the desired flying height and rotated through a range of angular positions. At each position a corrective force was applied to the assembly to restore it to the static position.

The corrective force is opposing both the side force and the static stabilizing moment, acting about the trapeze plot, due to the roll angle relative to the ground. This may be allowed for since the static stabilizing moment, M, is known from the experiment described in the preceding section.

The experiment was performed twice with a difference in the method of applying the corrective force. In Method 1 this was applied as a vertical force simply by hanging a small weight on the yardarm and moving it in or out until the static position was reestablished. This had been found to be successful with the thin jet model of Reference 1; it is tedious to apply, because the assembly takes a long time to settle to the static position and meanwhile is very susceptible to disturbance from random air currents. In Method 2 the correction is applied as a horizontal force by causing the assembly to deflect the thread of a suspended weight. The static position was found by moving the point of suspension toward or away from the assembly. The method has the merit that force thus applied is damping to the swing about the static position, which thus can be more rapidly found.

The two methods are illustrated in Figures 17 and 18. The applied force is converted to a moment about the trapeze pivot, the static moment is subtracted, and the residue is converted to an equivalent force at the base of the machine. The results are plotted in Figures 19 through 22 as a ratio of the lift (that is, as the angle χ), against ϕ, the angle of the ground board relative to the machine. The slope of these plots is the derivative χ_ϕ, which appears in the criterion for dynamic stability on page 6.

For the annular jet GEM, χ_ϕ is practically zero at heights less than the jet width and decreases to -0.167 at a height of 1.90cm.

For the plenum chamber GEM, χ_{ϕ} is positive at all heights, ranging from the value 0.143 at a height of 0.70 cm. to 0.80 at a height of 1.90 cm.

For the modified plenum, the observed value of χ_{ϕ} was 1.05 at a height of 0.70 cm.

Figure 23 shows the plenum chamber values of χ_{ϕ} plotted against h/a, the ratio of flying height to the beam of the machine. In Figure 24 the values of χ_{ϕ} for the annuler jet version are plotted against the height tc jet width parameter, h/G_{ϵ}, along with many other values collected in Reference 1.

The numerical values of Y/L and tan Ø for the annular jet GEM are listed in Table 5. Those for the plenum GEMs are in Table 6.

TABLE 5

SIDE FORCE DUE TO ROLL

ANNULAR JET MODEL GEM

Lift = 362 grams, i = 1.0 amp, h = 0.70 cm		Lift = 240 grams, i = 0.8 amp, h = 1.00 cm		Lift = 181 grams, i = 0.8 amp, h = 1.45 cm		Lift = 184 grams, i = 1.0 amp, h = 1.90 cm	
Y/L	tan Ø	Y/L	tan Ø	Y/L	tan Ø	Y/L	tan Ø
+0.0022	+0.0000	-0.0130	+0.0000	-0.0086	+0.0000	-0.0016	0.0000
0.0021	0.0170	0.0135	0.0147	0.0084	0.0148	0.0042	0.0170
0.0022	0.0340	0.0140	0.0294	0.0086	0.0295	0.0047	0.0340
0.0023	0.0510	0.0145	0.0440	0.0105	0.0295	0.0054	0.0510
0.0027	0.0612	0.0149	0.0599	0.0100	0.0442	0.0072	0.0681
0.0017	0.0000	0.0142	-0.0147	0.0127	0.0590	0.0032	0.0850
0.0017	-0.0170	0.0144	0.0294	0.0119	0.0590	0.0016	0.0000
0.0015	0.0340	0.0150	0.0440	0.0117	0.0740	+0.0012	-0.0170
0.0048	0.0510	0.0168	0.0590	0.0121	0.0886	0.0033	0.0340
		0.0130	0.0000	0.0084	0.0000	0.0043	0.0510
				0.0062	-0.0148	0.0061	0.0681
				0.0053	0.0295	0.0074	0.0850
				0.0064	0.0295		
				0.0048	0.0442		
				0.0045	0.0590		
				0.0041	0.0740		
				0.0085	0.0072		
				0.0064	0.0000		

TABLE 6

SIDE FORCE DUE TO ROLL

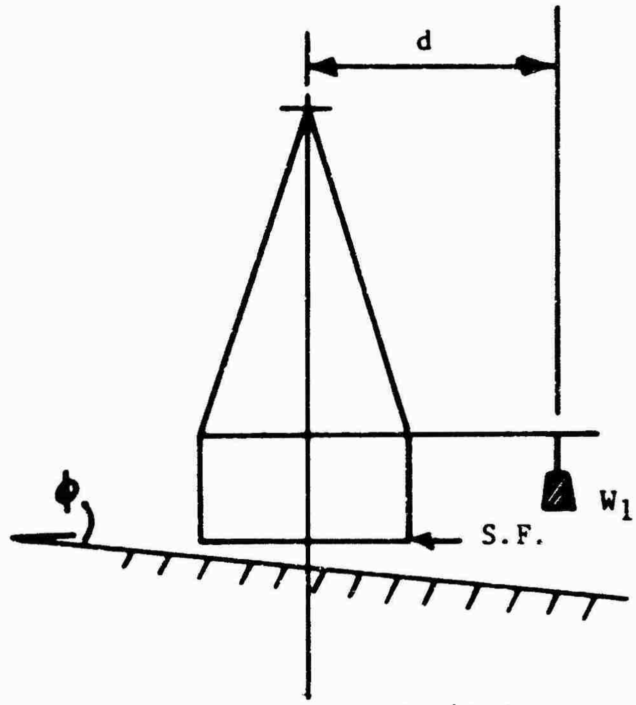
PLENUM MODEL GEM

Lift = 270 grams i = 0.8 amp h = 0.70 cm		Lift = 223 grams i = 0.8 amp h = 1.00 cm		Lift = 156 grams i = 0.8 amp h = 1.45 cm		Lift = 80 grams i = 0.8 amp h = 1.90 cm	
Y/L	tan Ø	Y/L	tan Ø	Y/L	tan Ø	Y/L	tan Ø
-0.0094	-0.0592	+0.0041	+0.0102	+0.0057	+0.0034	+0.0025	+0.0000
0.0166	0.0427	0.0078	0.0272	0.0074	0.0136	0.0184	0.0168
0.0022	0.0322	0.0124	0.0442	0.0144	0.0360	0.0222	0.0168
+0.0002	0.0247	0.0188	0.0613	0.0215	0.0476	0.0184	0.0168
0.0025	0.0071	0.0239	0.0785	0.0288	0.0647	0.0349	0.0336
0.0178	0.0017	0.0032	0.0102	-0.0116	-0.0240	0.0456	0.0504
0.0097	+0.0220	-0.0013	-0.0062	0.0227	0.0371	0.0399	0.0504
0.0132	0.0443	0.0046	0.0238	0.0311	0.0545	0.0532	0.0672
0.0188	0.0572	0.0106	0.0408	0.0063	0.0034	0.0025	0.0000
0.0066*	0.0102	0.0127	0.0580			-0.0036	-0.0168
0.0108	0.0272	0.0027	+0.0102			0.0228	0.0336
0.0132	0.0442					0.0165	0.0334
0.0153	0.0613					0.0387	0.0504
0.0070	0.0102					0.0525	0.0672
0.0043	-0.0068						
0.0014	0.0238						
-0.0008	0.0408						
+0.0070	+0.0102						

MODIFIED PLENUM MODEL GEM

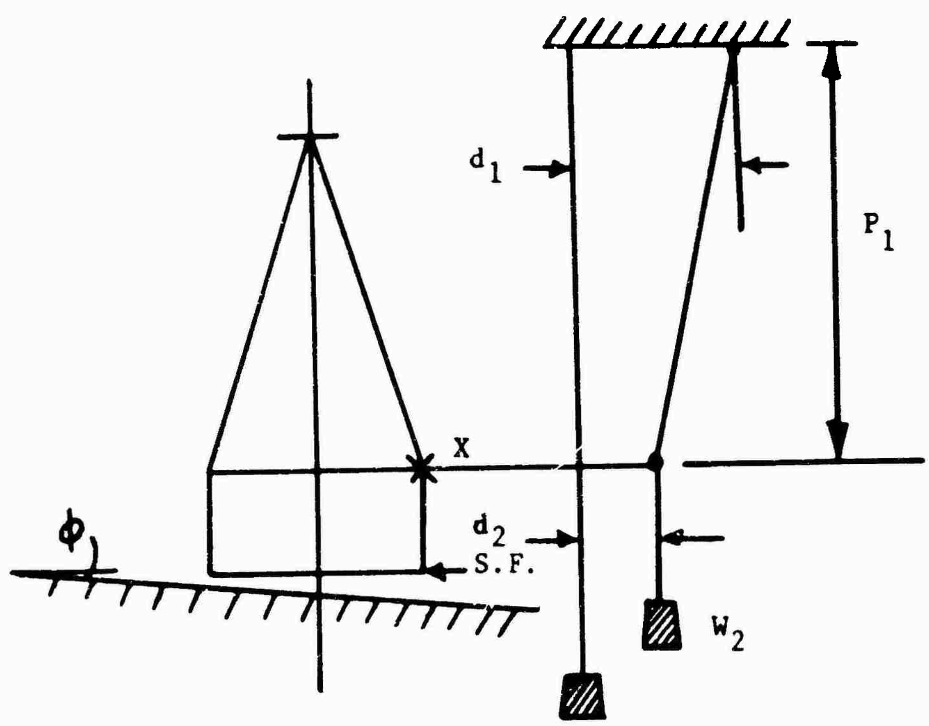
Lift = 207 grams
i = 1.0 amp
h = 0.70 cm

Y/L	tan Ø
0.0089	0.0000
0.0187	0.0170
0.0375	0.0340
0.0557	0.0510
0.0193	0.0170
0.0374	0.0340
0.0627	0.0510



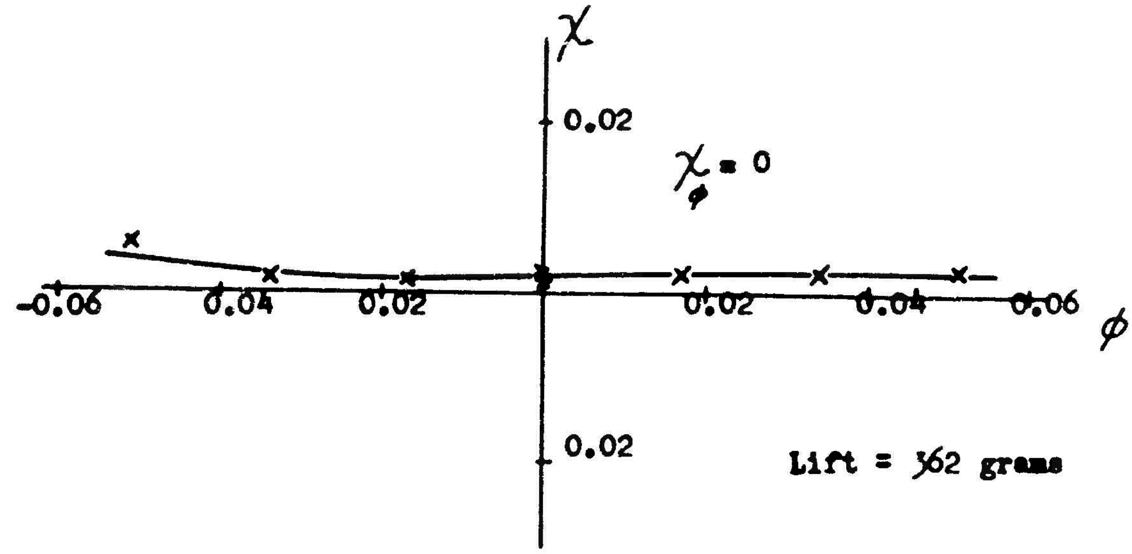
Applied moment = W_1 (d)

Figure 17. Measurement of Side Force - First Method

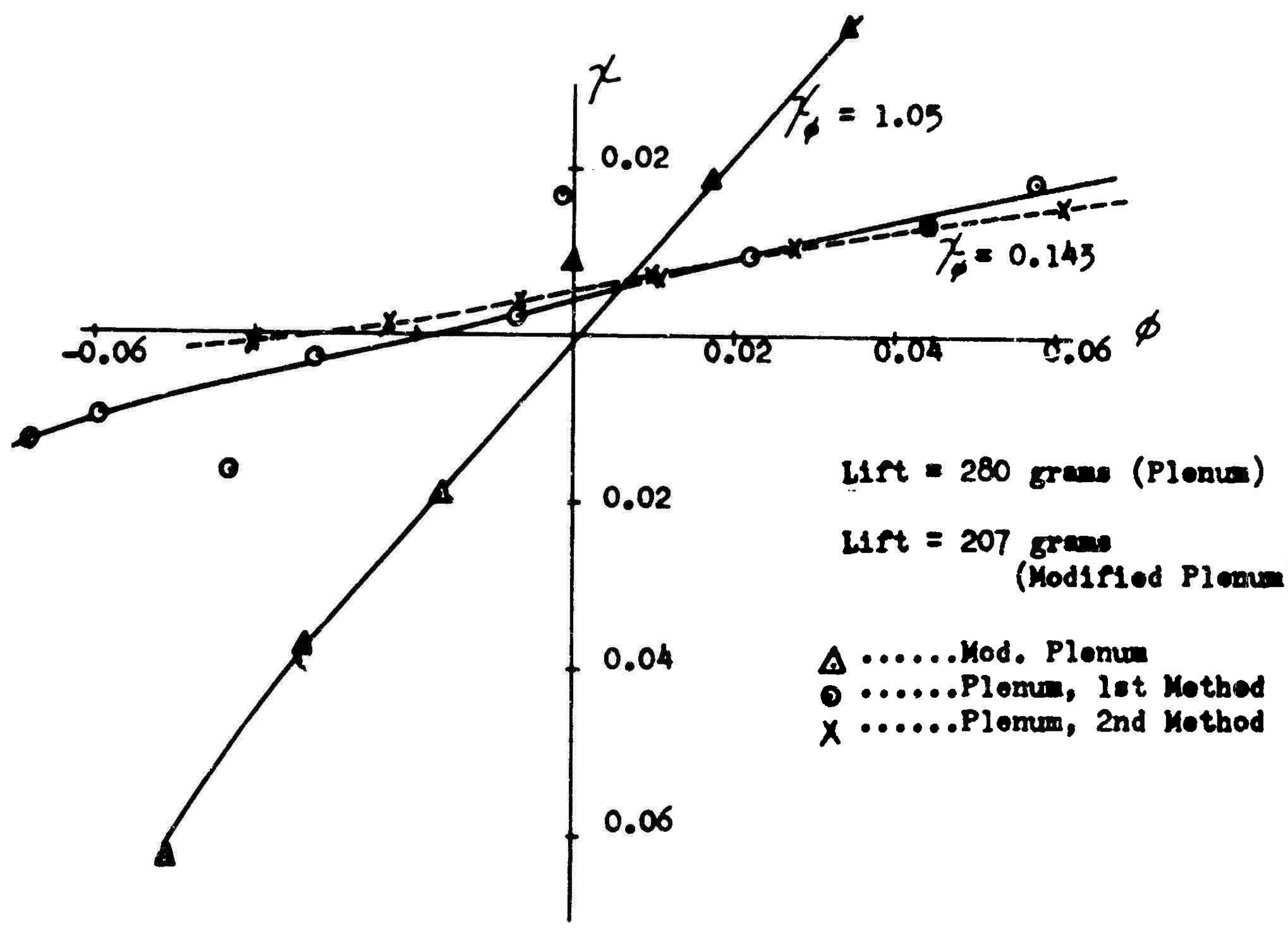


Force applied at X = $W_2\ (d_1 - d_2)/P_1$

Figure 18. Measurement of Side Force - Second Method

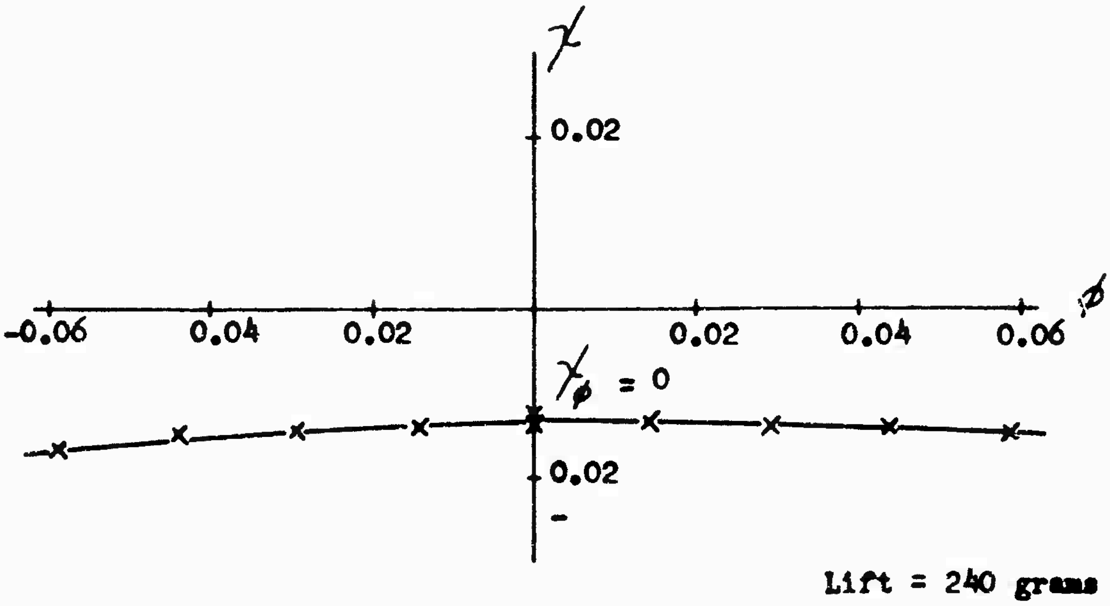


ANNULAR JET MODEL GEM

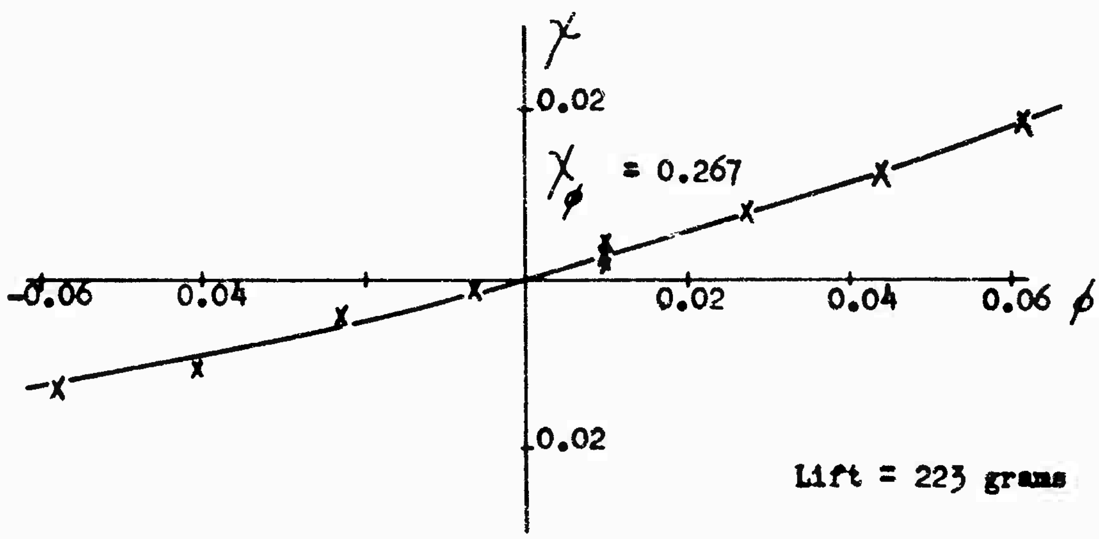


PLENUM AND MODIFIED PLENUM MODEL GEMS

Figure 19. Side Force Due to Roll for h = 0.70 (h/a = 0.035)

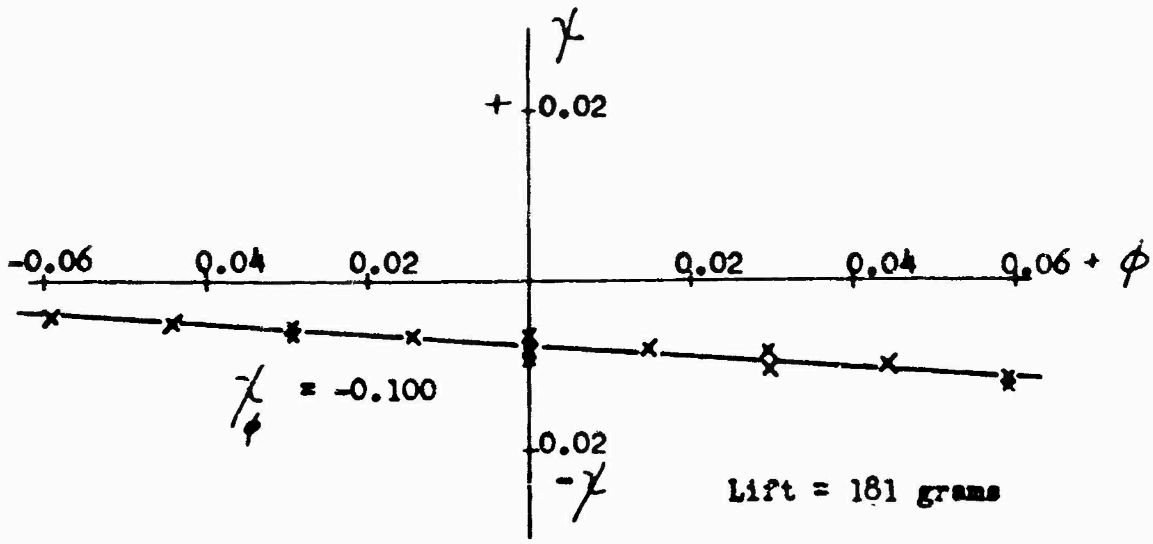


ANNULAR JET MODEL GEM

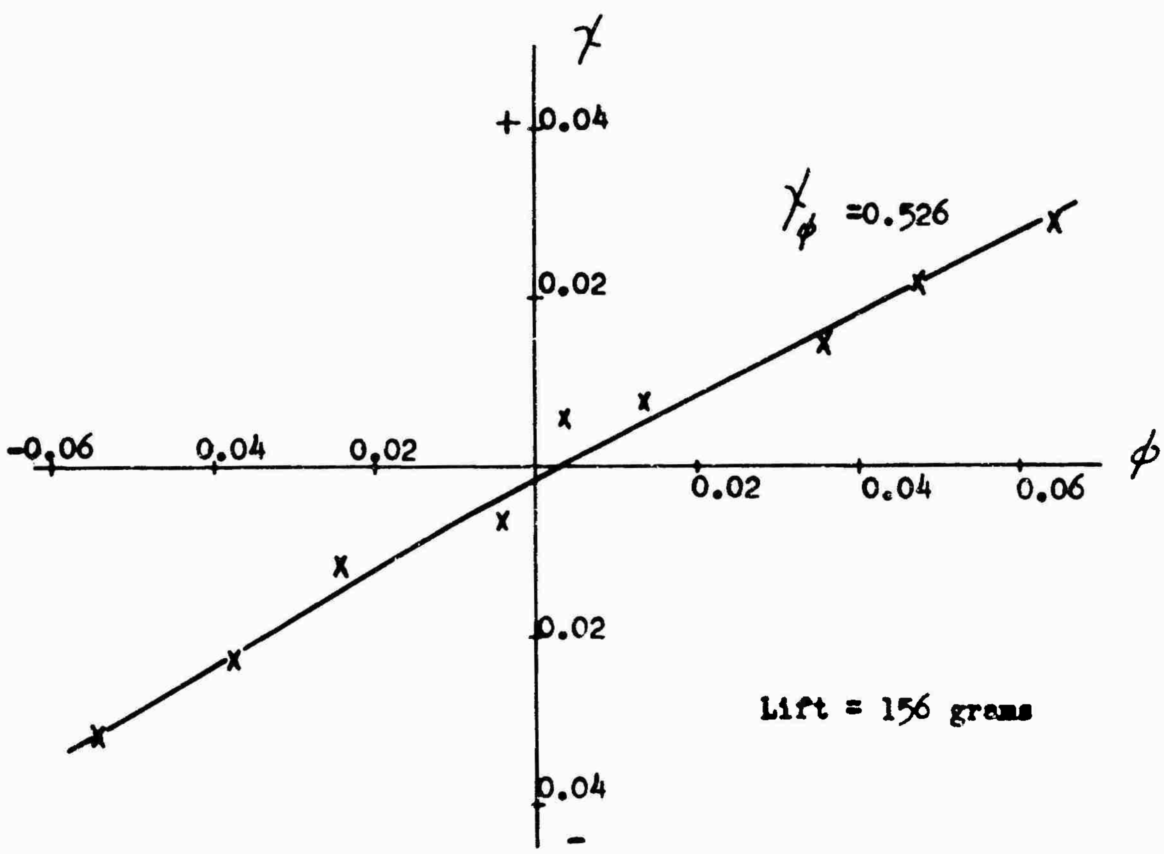


PLENUM MODEL GEM

Figure 20. Side Force Due to Roll for h = 1.00cm. (h/a = 0.048)



ANNULAR JET MODEL GEM



PLENUM MODEL GEM

Figure 21. Side Force Due to Roll for h = 1.45cm. (h/a = 0.060)

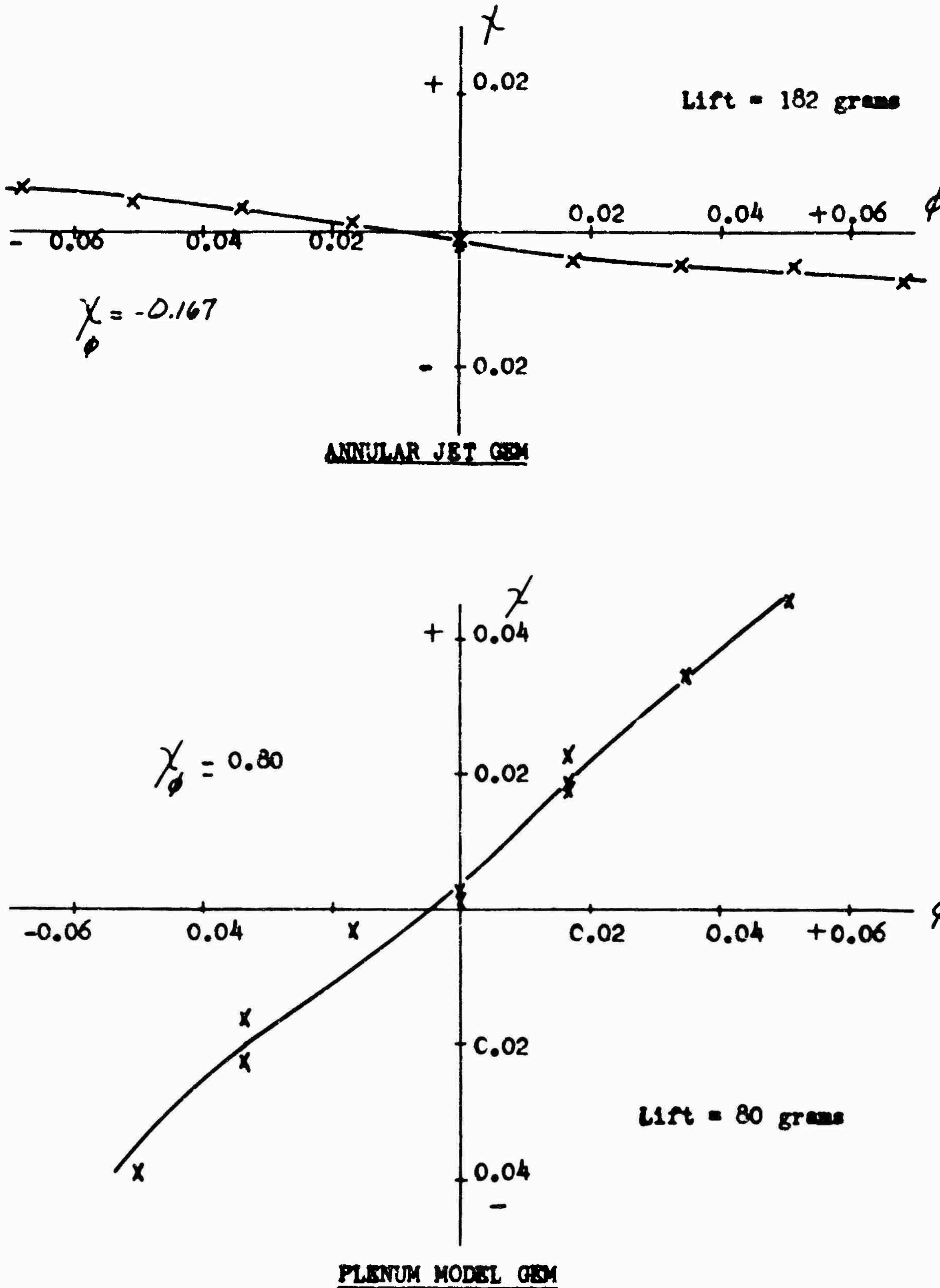


Figure 22. Side Force Due to Roll for h = 1.90cm (h/a = 0.091)

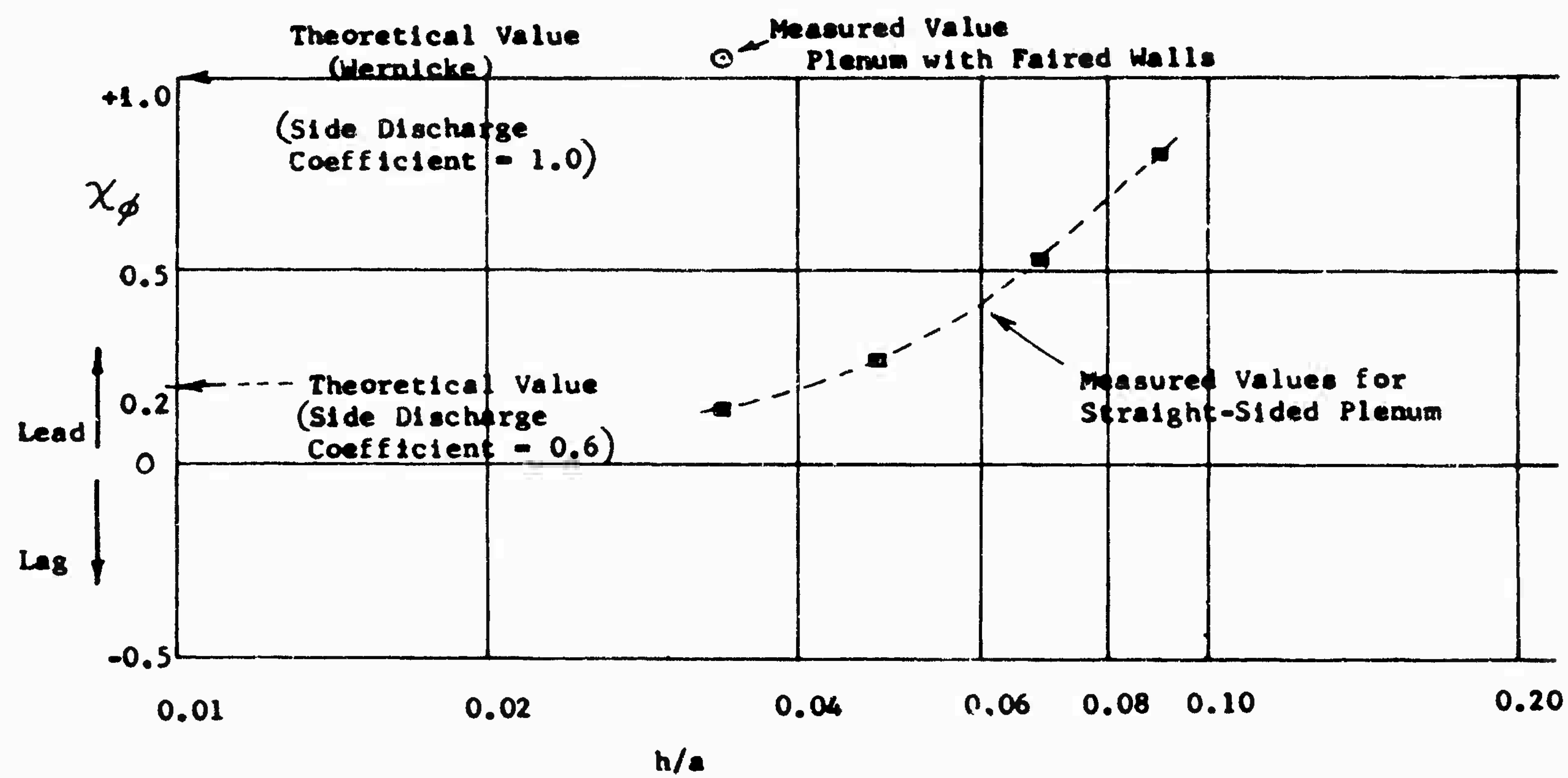


Figure 23. Effect of Hover Height on Side Force Due to Roll - Plenum GEMs

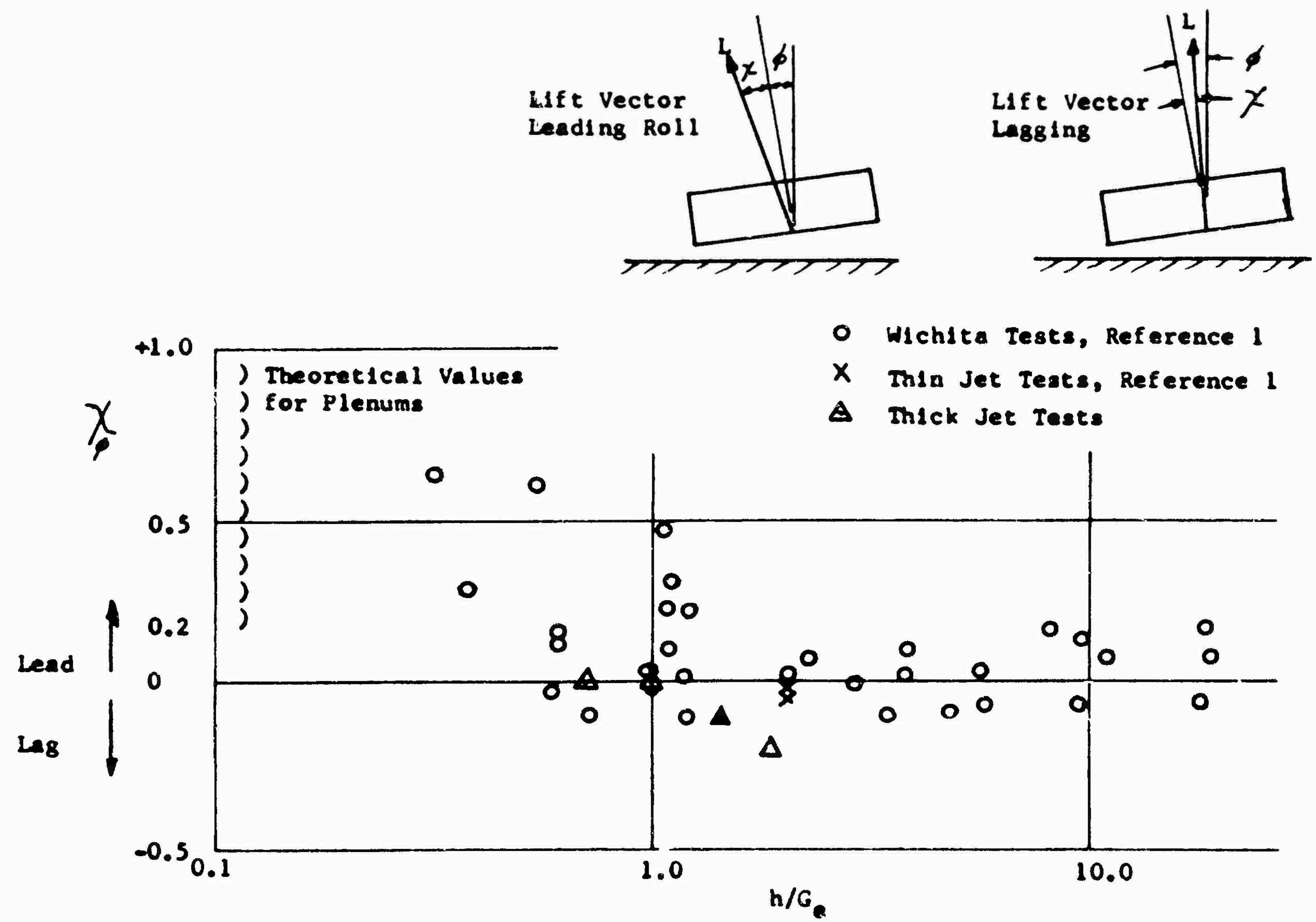


Figure 24. Comparison of Measured Values of Side Force With Data From Reference 1 - Annular Jet GEMs

Quasi-Free Oscillation Measurements

If the GEM were pivoted about an axis which coincided with the free roll axis P of Figure 1, the pivots should apply no constraint to the rolling motion but should merely serve to suppress heave, yaw, pitch, and fore and aft motion. If the pivot axis were free to move sideways and were located below the axis P, it should not constrain the motion but should move sideways with the GEM in the motion. If the pivot axis were above the axis P, it should move sideways in opposition to the GEM.

This was demonstrated for the thin annular jet GEM and is described in Reference 1. The GEM was pivoted in the trapeze which was free to swing sideways. The angle between the GEM and the trapeze was measured by a virtually frictionless electrolytic potentiometer. The angular position of the trapeze was measured by means of a conventional low-friction potentiometer, which also gave the lateral position of the pivot axis. The oscillation was excited by releasing the GEM from a displaced position, and four or five cycles were recorded in each case. When the pivot was low it moved sideways with the GEM, and when it was high it moved in opposition. By a comparison of the amplitudes, a position for zero movement, that is the position of the axis P, was determined as 15.5 cm. above the CG in the particular conditions of the test.

The attempt was made to repeat this experiment with the thick annular jet GEM and the plenum chamber GEM. In both cases the oscillation with the pivot low (position 1 of Figure 2) showed the pivot axis moving sideways with the GEM, though only two or three cycles were discernible. At the highest available pivot (position 5) the oscillation could not be excited in either case. Instead, the whole assembly swung about the axis of the trapeze more or less as a simple pendulum. The reason for this is apparent from consideration of the static stability of these versions of the GEM. For the thin jet of Reference 1, the nondimensional stability $\bar{M}\phi$ ($-M\phi/La$) was 0.97. For the thick jet the corresponding value was only 0.225, and for the plenum it was almost zero. Therefore, disregarding the influence of $X\phi$ on the position of the axis of rotation, it is evident that the axis is very much higher in the machine for both of the present versions. To get above it, in order to show the antiphase characteristic, a superstructure of more than 60 cm. in height would have been necessary, together with a very much taller trapeze and test stand. It was considered that the feasibility of these alterations was doubtful and was certainly not capable of being accomplished within the budget of this contract.

The GEMs in Free Flight

As a demonstration of the dynamic stability of this model GEM in both of its versions, it was set down on the laboratory floor and flown round the room. The motor current was supplied by a very flexible twin pair of wires attached to one end of the machine at approximately the height of the CG and carried by the operator on a wand, so that he could exercise some control in pitch and yaw without exciting the roll oscillation.

Both versions of the GEM were dynamically quite stable in both the low and the high CG positions. At the extra-high CG position, with its additional weight, the power available would lift the machine only a few millimeters and consequently only very small roll angles could be displayed without contact with the floor, but there was no doubt that both versions of the machine were stable over these small displacements.

Qualitatively, therefore, the dynamic stability is little affected by the height of the CG, and there is little difference in character between the two types of GEM despite the different ways in which this is produced. The fact that the Plenum GEM was not stable **statically** was not apparent from its behaviour in flight, and it is evident that the rotation of the lift vector to produce positive side force is an important factor in providing the stability in flight.

REFERENCES

1. Walker, Norman K., and others; The Effect of the Vertical Position of the Center of Gravity on the Stability of an Annular Jet Ground Effect Machine, TCREC 62-101, U. S. Army Transportation Research Command, Fort Eustis, Virginia, December 1962.

2. Wernicke, K. G. Forces Developed by a Plenum Chamber Type Ground Effect Machine at Zero Forward Speed, Propulsion Research Note, BELL Aerosystems Company, Fort Worth, Texas, June 1960.

3. Carmichael, Bruce H., and others, State of the Art Summary of Air Cushion Vehicles, Publication No. U-926, AERONUTRONIC Division of Ford Motor Company, Newport Beach, California, June 1960.

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APPENDIX

THE ROLL STABILITY OF A SKIRTED GEM

WITH THE SKIRT IN CONTACT WITH THE GROUND

INTRODUCTION

Discussion of the stability of a skirted Ground Effect Machine in free flight is incomplete without some consideration of what happens when the skirt makes contact with the ground.

When this happens it is fairly evident that the system of forces for the free flying GEM as described in the "Simple Theory" section of this report does not apply. We must, then, have a total or partial sealing of the air against escape on that side and the indroduction of a force or combination of forces applied by the ground to the skirt.

The practical GEM is likely to be of the annular jet type with skirts or trunks extending the jet downward. As shown in the theory and in the tests described in this report, such a GEM experiences a static stabilizing moment and a lift force which is always normal to its base and central in the machine. Its motion in roll is as if it were swinging like a pendulum from a supporting axis located at a distance above the center of gravity. Therefore it is always moving sideways toward the low side when displaced in roll. If the ground or other obstacle is struck, the reaction upon the GEM must always include a horizontal component of force which opposes the motion and consequently tends to increase the angle of roll and overturn the machine. Upward vertical components, if present, will tend to right the machine. It is therefore of interest to examine cases where the ground reaction is entirely horizontal because these are likely to be severe.

SUMMARY AND CONCLUSIONS

(1) The GEM moving sideways with one skirt just touching the ground and encountering a step of height 't' with a coefficient of friction 'μ' will fold the entire skirt and bump its hard structure on the step if $\mu t/s$ exceeds a critical value μ_r where

$$\mu_r = \bar{M}\phi \cdot \frac{2h}{s} \cdot \frac{a}{l_w + 2h} .$$

Otherwise it will recover to normal flight.

(2) Bumping the hard structure and digging it in, the GEM will overturn if the kinetic energy is sufficient.

(3) If the hard structure does not dig in but rebounds or slides, the vertical reactions of the grouhd will, in general, exert strong righting moments on the machine. The special case where there is no bump is the same analytically as that in which the machine is initially at rest with one side pressed against an incline. The steepest such incline is one whose slope is equal to s/a and the GEM will slide uphill or stick according as u is less or greater than a critical value $\mu_s = 2h/s$. It will roll into the ground, or off it, according as μ is greater than or less than u_r as defined in (1). These two criteria determine four distinct responses for GEMS in this situation.

If the slope is less than s/a the critical value of μ_r is unchanged, but μ_s is increased. In particular, on level ground, μ_s is increased by unity to a value of $2h/s + 1$.

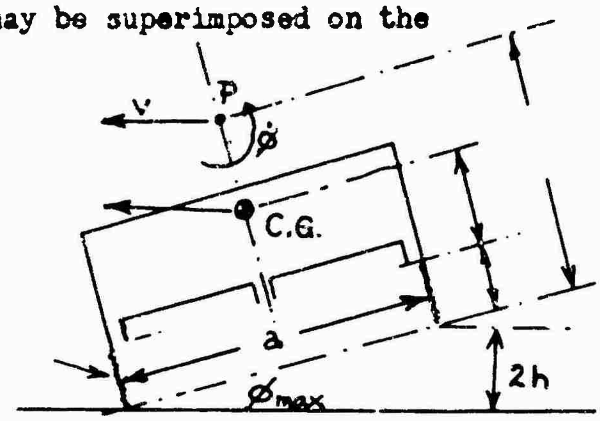
THEORY

The cases considered are all presumed to develop from free flight with the GEM rolling at a mean height h. The free flight roll is as a pendulum swinging about the axis P located above the CG of the machine. By definition the swing is limited to the amplitude ϕ max. where

$$\phi_{max} = 2h/a. \tag{1}$$

An arbitrary velocity sideways (=v) may be superimposed on the roll.

With the notation of Figure 1 of the main text, let s be the length of skirt.



For a thin annular jet

$$Y\dot{\phi} = 0 \tag{2}$$

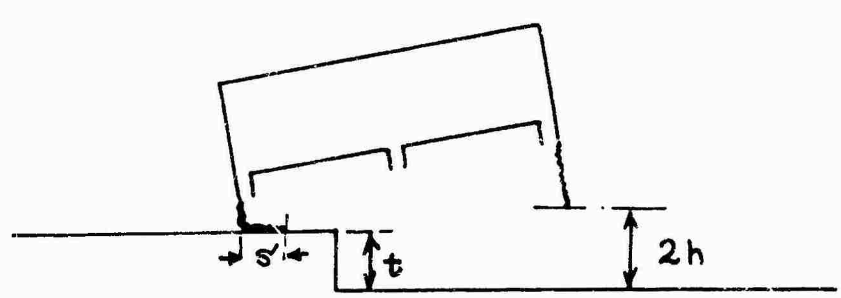
and the axis P is at a position given by

$$l_p = -I/MY\phi \tag{3}$$

and

$$\dot{y}_{skirt} = v - I/MY\phi \cdot \dot{\phi}. \tag{4}$$

In this condition the GEM encounters a step of height 't'



which causes the skirt on the low side to fold part of its length, 's' horizontally along the step.

The skirt is presumed to make an effective seal with the ground when in contact with it. The pressure inside does not increase further with roll angle. For the lift to remain constant supporting the weight of the machine the height at the other side must remain fixed at 2 h. The pressure difference across the base is governed by the strength of the central stabilizing jet. Let us suppose that this was just sufficient to produce the stabilizing moment.

$$M = M_{\phi} . \phi_{max} = M_{\phi} . 2h/a .$$

The jet pressure is applied to the folded part of the skirt and this is transmitted to the ground. As the skirt slides over the ground a horizontal frictional resistance F is developed.

$$F = \mu P_b . s' \text{ (per unit length)}$$

$$= \mu \frac{W}{a} . s'$$

$$= \mu \frac{W}{a} (t - 2h + a\phi) \qquad \text{for any angle } \phi$$

and we assume that this can be transmitted to the GEM thru the unfolded part of the skirt.

Taking moments about the CG, and assuming that the friction force will act parallel to the base,

$$I/g. \ddot{\phi} = M + F (l_w + s - s')$$

$$= M + u \frac{W}{a} s' (l_w + s + 2h - t)$$

$$= M + \mu W \left\{ l_w + s. + 2h - t \right\} \left\{ \phi - \frac{2h - t}{a} \right\}$$

$$= \mu W (l_w + s + 2h - t) \left\{ \phi - \frac{2h - t}{a} + \frac{M}{\mu W (l_w + s + 2h - t)} \right\}$$

$$\therefore \ddot{\phi} > o \quad \text{if } \phi > \left\{ \frac{2h - t}{a} - \frac{M}{\mu W (l_w + s + 2h - t)} \right\}.$$

This is true initially because

$$\phi = \phi_{max} = 2h/a .$$

Therefore,

$$\ddot{\phi} > o; \qquad \text{thereafter if}$$

$$t/a > \frac{-M}{\mu W\,(\,l_w + s + 2h - t\,)} = \frac{-M}{\mu W\,(\,l_w + 2h\,)} \quad \text{approx.}$$

(Since s - t is small compared with l_w + 2h.)

That is, if

$$\mu t/a > \frac{-M}{La} \cdot \frac{a}{(lw + 2h\,)}.$$

This result shows that the GEM at full roll, $\phi = \phi_{max}$ and $\gamma = o$ encountering the step of height t, will fold its skirt and bump its hard structure if

$$\frac{\mu t}{a} > \frac{-M_\phi \;\cdot\; \phi\,max}{La} \cdot \frac{a}{(\,l_w + 2h\,)}$$

that is

$$\frac{\mu t}{a} > +\bar{M}_\phi \cdot \frac{2h}{(\,l_w + 2h\,)}$$

or $$\frac{\mu t}{s} \quad \bar{M}_\phi \;\cdot\; 2h/s \;\cdot\; \frac{a}{(\,l_w + 2h\,)}.$$

For the test model flying at h = 1cm. and,say, s= 2cm., a = 21cm.,

$\bar{M}_\phi$ = 0.25, l_w + 2h = 9.05cm. (low CG) or 15.1cm (high CG).

Therefore the GEM will bump hard structure if

$$\mu t > \frac{0.25 \times 2 \times 21}{9.05} \text{ (low CG) or } \frac{0.25 \times 2 \times 21}{15.1} \text{ (high CG)},$$

i.e., $\mu t >$ 1.15cm (low CG) or 0,7cm. (high CG).

Suppose μ = 0.25.

Then the GEM model will bump if t > 4.6cm. (low CG) or if t > 2.8cm. (high CG).

Since the hard structure clearance , h + s = 3cm, a step higher than t = 3cm will hit the sidewall. But the low CG GEM will recover normal flight from all steps up to t = 3cm; and at high CG; up to 2.8cm. (of course if $u = 1$ the initial step heights are reduced to one quarter).

Cases when $\mu t/a > \bar{M}\phi \cdot \left(\frac{2h}{l_w + s}\right)$.

As shown in the preceding section, when this condition applies the GEM does not recover normal flight, but accelerates its roll ($\dot{\gamma} > 0$) until all the skirt is folded and the hard structure bumps down on the step.

What happens next depends upon various circumstances; the nature of the ground, the initial conditions, and the values of the terms which govern the angular acceleration.

If the nature of the contact is such that the hard structure digs in and is brought to rest, the GEM will topple over if there is enough kinetic energy to lift the CG over dead center. The lift and moment of the GEM will fall to zero as soon as the high side is raised much above 2h.

The kinetic energy may be evaluated by integrating the equation of motion on page 2 and adding the energy of the translating velocity.

$$I/g\, \dot{\phi}^2 = \mu W (l_w + s) \left[\phi^2/2 - \left(\frac{2h - t}{a} - \frac{M}{uW (l_w + 2h)} \right) \phi \right] + A$$

if $I = WK^2$

$$K.E. = \frac{1}{K^2} (K^2 + l_w^2 + a^2/4) \cdot \mu W_g (l_w + 2h) \Big[\quad \Big]_{\phi max}^{\phi} + Wv^2/2$$

Where $\phi = \frac{2h - t + s}{a}$ $\qquad \phi_{max} = \frac{2h}{a}$

$$P.E. = W_g \left\{ a/2 \sin\phi + l_w \cos\phi \right\}_{\phi\, max}^{\phi}$$

and GEM topples if K.E. $>$ P.E.

If the nature of the ground is such that the hard structure is not brought to rest by the contact, the ensuing motion is complicated in general.

An interesting simple case occurs when the contact is made at zero angular velocity. If the angular acceleration is also zero the attitude will not change and the machine will slide or stick in this attitude.

This is a limiting case of the motion previously considered if we take t = s, the maximum height of step which can be encountered in this way. For zero angular acceleration the friction μ must have a critical value, μ_r

$$\mu_r = \overline{M}\phi \cdot \frac{2h}{s} \cdot \frac{a}{l_w + 2h}.$$

Sliding will occur if the side force $L\phi > F$.

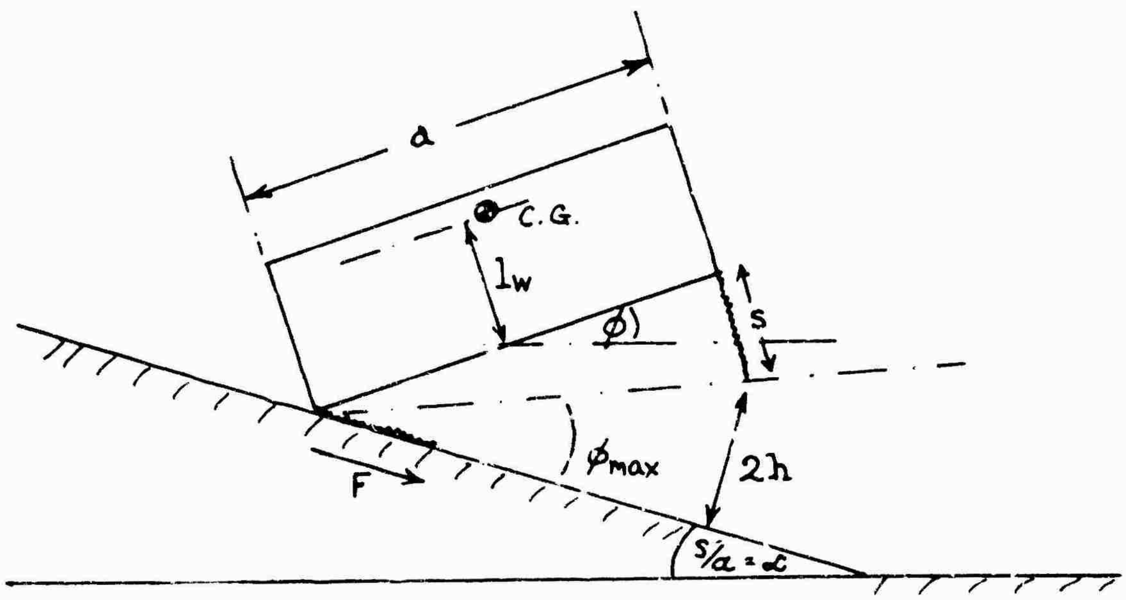
This will be so if μ is less than the critical value μ_s

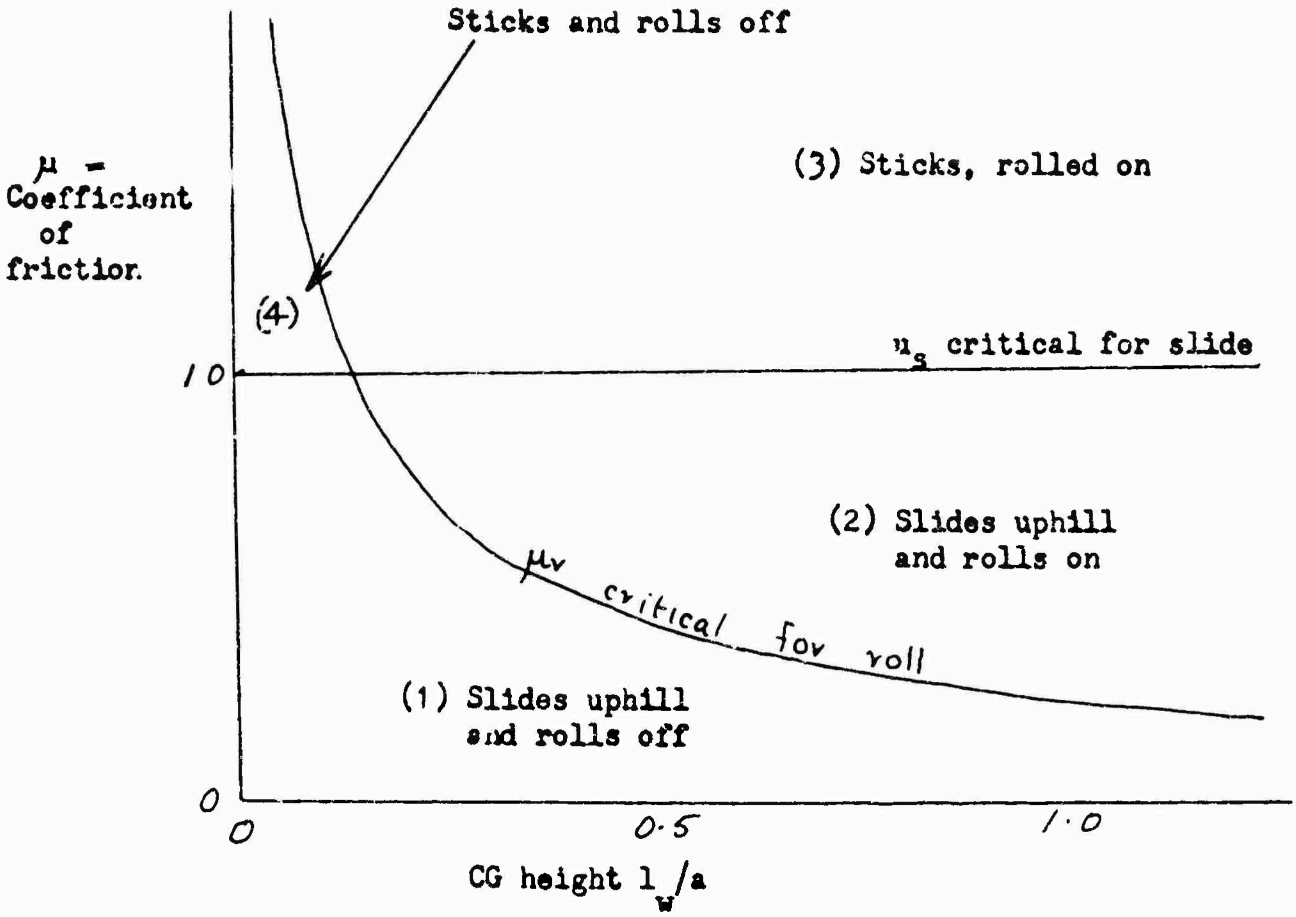
where $L\phi = F = u_s \cdot W/a. \; s;$

i.e., when $\mu < \mu_s = 2h/s.$

The form of these expressions is unchanged if we replace the step of height s with a continuous incline of slope s/a.

This is now the case of the GEM lying against a hillside of slope,
$x = s/a.$





Climb or stick boundaries for GEM on hillside
(Curve for model GEM at h = 1cm, assumed s = 2cm)

This shows that for any skirted GEM there are 4 regions of possibility:

(1) $\mu < u_r$ and μ_s

The machine will slide uphill, rolling off and recovering free flight with skirt clear of ground. If a control moment is applied in the positive sense of the machine can be made to climb the gradient. If 2h s it can do this in free flight anyway, so there is no advantage in putting the skirt on the ground. By the same token, there is little penalty other than a change of trim and control moment.

(2) $\mu_r < u < s_s$

The machine will slide uphill, trying to roll into the hillside. Reaction from the ground, and loss of lift from raising the trailing side, must restrain this roll, though perhaps not continuously.

This happens with fairly high CG positions and high (fairly) values of μ

(3) $\mu_r < \mu_s < \mu$

The machine cannot climb, but remains stuck with its edge pressed into the hillside.

(4) $\mu_s < u < \mu_r$

The machine cannot climb the hill but rolls down it, thus regaining free flight.

The GEM's behaviour against a slope less than s/a can be derived easily by rotating the picture through the change of slope.

The moments about the CG are unaffected by this change. Therefore, as before,

$$\mu_r = \bar{M}\phi \cdot \frac{2h.}{s} \quad \frac{a}{l_w + 2h}$$

and the skirt remains pressed to the ground if μ exceeds μ_r. Assuming that the machine was placed in this attitude initially, it will remain so, sliding laterally if $\mu_r < \mu < \mu_s$ and stationary if $\mu_r < \mu$, $\mu_s < \mu$. It will get up and fly normally if $\mu < \mu_r$.

This treatment is deliberately oversimplified, but even so illustrates the complexity and general form of the phenomena involved.

In particular the neglect of s - t, relative to L + 2h may be incorrect for a machine of slightly different geometry, and we have ignored altogether the forces due to deforming the skirt which will produce minor effects on lift but an appreciable restoring moment.

An interesting effect which will be examined further in a later report, is found by tapering, or reducing the periphery of the skirt. This is common practice, since the skirt is then stabilized to a more easily defined shape by the base pressure. Now if the skirt folds the ground supports a download which was previous tensioning the skirt. Hence the Center of Pressure shifts to the downward edge, and a considerable additional stabilizing moment, increasing with roll angle, is developed, giving much more favorable results. We believe that this phenomenon explains the comparatively satisfactory results achieved in practice, with skirts of rubberised fabric, which should have a rather large coefficient of friction.